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Research Note 83-58, Final, Feb. 80  
DA ERO 78-G-018  
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Research Note 83-58

AD A137180

FEED FORWARD PROGRAMMING OF CAR DRIVERS' EYE MOVEMENT

BEHAVIOR : A SYSTEM THEORETICAL APPROACH

FINAL TECHNICAL REPORT VOLUME I

Amos S. Cohen  
SWISS FEDERAL INSTITUTE OF TECHNOLOGY

BASIC RESEARCH



U. S. Army

Research Institute for the Behavioral and Social Sciences

February 1980

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Research Note 83- 58	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle)  FEED FORWARD PROGRAMMING OF CAR DRIVERS' EYE MOVEMENT BEHAVIOR: A SYSTEM THEORETICAL APPROACH FINAL TECHNICAL REPORT VOLUME I		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report, Vol I Nov 77 to Feb 80
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s)  Amos S. Cohen		8. CONTRACT OR GRANT NUMBER(s)  DA ERO 78-G-018
9. PERFORMING ORGANIZATION NAME AND ADDRESS Swiss Federal Institute of Technology Department of Behavioral Science, Zurich		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 6.11.02A 2Q161102B74F
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Research, Development and Standardization Group (UK), Box 65, FPO New York 09510		12. REPORT DATE February 1980
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) US Army Research Institute for the Behavioral and Social Sciences, 5001 Eisenhower Avenue, Alexandria, Virginia 22333		13. NUMBER OF PAGES 216
		15. SECURITY CLASS. (of this report)  Unclassified
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Spatial discontinuity; temporary discontinuity; visual communication; foveal vision; peripheral vision; parafoveal information; eye fixation rates		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Vol I of the final report contains accounts of contemporary research and theory of eye movement behavior. Of primary interest in this research is the visual input occurring during car driving that facilitates control via develop- ment of a concept of the ever-changing environmental conditions in driving a motor vehicle. In investigating a driver's visual input, it is important not only to consider information available at every moment, but information actually used in steering. The analysis of a person's eye movement behavior can distinguish between available information and the specific part of the		

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environment upon which a driver actually fixates. Essential information input is obtained from those parts of the visual environment which are successfully fixated upon.

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## FOREWORD

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The research described in this Technical Report, "Feed-Forward Programming of Car Drivers' Eye Movements: A System Theoretical Approach", was performed under Army Project Number 2Q161102B74D by Amos S. Cohen (Vol I) and by Amos S. Cohen and Rene Hirsig (Vol II) of the Swiss Federal Institute of Technology, Department of Behavioral Science, Zurich.

The research was based upon theory of eye movement behavior during driving in predicting the car driver's future or forward eye fixations in their successive order. Of primary interest was the visual input during car driving that facilitates control via development of a concept of ever-changing environmental conditions. Car drivers' eye fixations were registered when driving a car on the road and when viewing a slide in the laboratory which showed the same traffic situation. It was determined experimentally that an analysis of a person's eye movement behavior can distinguish between available information and the specific part of the environment upon which a driver actually fixates. There are ready implications, not only for the driving situation but for perceptual processes as necessary preconditions for carrying out goal-oriented activities.

I would like to extend my appreciation to Dr. William H. Helme and to Dr. Arthur J. Drucker for acting as the COR for this research during their tours as Scientific Coordinator - Europe.

JOSEPH ZEIDNER  
Technical Director

## FEED-FORWARD PROGRAMMING OF CAR DRIVERS' EYE MOVEMENTS

### BRIEF

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#### Requirement:

In investigating a driver's visual input, it is of importance not only to consider the information actually used in steering an automobile. To achieve this goal, the analysis of a person's eye movement behavior provides a useful method for distinguishing between the available information and the specific part of the environment upon which a driver actually fixates. However, if one is going to analyze the driver's eye movement behavior, he must know the essential characteristics of visual search as manifested by the patterns of fixations or the respective sequences. Therefore, the requirement for this research was to delineate functional relationships between successive eye-movement properties of human subjects in car driving situations and to develop mathematical functions in terms of time-discrete process based upon a model by Hirsig.

#### Procedure:

Car drivers' eye fixations were registered when driving a car on the road and when viewing a slide in the laboratory showing the same situation as a basis for data collection designed to accomplish the following: (a) determine functional relationships between successive eye movement properties in complex vs. simple driving situations, (b) ascertain individual differences, (c) validate the Hirsig models and relate them to different classes of traffic, (d) determine effects of learning on these functions, (e) relate eye movements to experience, personality and field dependency, (f) develop higher order model subsuming the individual models, and (g) test model-based environmental design and guidance procedures.

#### Findings:

In the first major experiment of the research, described in Vol I, eye fixations of drivers were analyzed when encountering and passing an unexpected road obstacle requiring a detour. The fixation patterns were compared with patterns from a laboratory sample of drivers observing photos of the same scene. The results shows marked differences directly related to driving path. The pattern sequences in the actual driving condition were then analyzed, yielding clear confirmation of the central hypothesis: eye movement behavior follows an anticipatory program in which a schema of search leads to selective information input and processing which continuously updates the schema and elicits a motoric behavior sequence.

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Chapter 1

I N T R O D U C T I O N

## 1. PERCEPTION AND PURPOSEFUL ACTIVITY

The perceptual processes are necessary preconditions for carrying out goal oriented activities. This general statement is supported by the fact that goal oriented activity does not only mean action but reaction, that is an interaction between the human being (or animal) with his environment. The environment, on the other hand, includes objects and/or other people (or animals). When using other words, it can be stated that each purposeful activity is carried out on the basis of prior information input and its adequate processing. Otherwise, only random action might be expected to occur without regard to the environmental condition rather than the purposeful reactions to ongoing events that is actually observed.

Goal oriented activity involves a dynamic process of self-adaptation to dynamic changes occurring in the environment. These are caused, from the egocentric point of view, partly by their own activity and partly by physical changes occurring in the environment. At the same time a person is continuously striving to accomplish his own goals.

In order to achieve his own goals, a person must consider two main categories of variables. The first of these is related to the dynamics of environmental conditions and the

second one to the capacities of the person. Even though this view suggests a rather simple relationship between the two variables, it is difficult to empirically define this relationship in such a way that it would be valid for all daily situations. The main difficulty is related to the complexity of the perceptual, as well as that of the motor processes. Furthermore, the information picked up may not immediately lead to a motor response. This information may first be processed and then stored and only subsequently be manifested as a motor response. The assumed time between the moment when the information input occurred and when the particular motoric response occurs makes it difficult to determine the causal relationship between information input and the motor activity. The identification of this relationship is further complicated by two conditions. First, it can be assumed that each "package" of information input is not necessarily associated with a motor response. This suggestion is supported by the fact that the rate of information input might be greater than the rate at which motor responses can be made. Second, the postulated time delay between information input and reaction is assumed to have not a constant but rather a variable value. Thereby, one has clearly to distinguish between reaction time, i.e., the minimum time needed for movement production and the time span through which one is voluntarily planning his future actions, i.e., anticipation (see chapter 3).

These considerations serve to emphasize that at the present stage of research it is hardly possible to determine a general model describing the relationship between information input and motor activity. Nevertheless, a better understanding of sensory-motor relationships must be considered as an important long-term goal which is of importance not only to advance the theory but also because of the possibility of potential applications. Therefore, at the present state of research it is necessary to investigate the mechanisms underlying perceptual, as well as motor processes in daily situations. This should facilitate the treatment of the interdependence of these factors. The focus of the following discussion will be sensory processing in general, and vision (i.e., eye movement behavior) in particular.

## 2. GOALS TO BE CONSIDERED IN THE FOLLOWINGS

Of primary interest is the visual input occurring during car driving that facilitates control via development of a concept of the ever changing environmental conditions. In investigating a driver's visual input it is of importance not only to consider the information available at each moment, but particularly the information actually used in steering an automobile. To achieve this goal the analysis of a person's eye movement behavior (i.e., the patterns of his fixations)

provides a useful method for distinguishing between the available information and the specific part of the environment upon which a driver actually fixates. The general idea of this research method is that essential informational input occurs from those parts of the visual environment which are successively fixated. This issue will be discussed in chapter 2 in general and in chapter 4 for the particular situation of car driving.

The importance of adequate visual input for correct driving has quantitative as well as qualitative aspects. First, the major part of the information that the driver picks up is visual. The other senses, of course, also contribute relevant information but they play a rather modest role, i.e., in comparison to vision. From the qualitative point of view, secondly, only vision provides information concerning events occurring at great distances, whereas the other senses are generally limited to the immediate surroundings. As a consequence, only vision is the adequate modality for acquiring relevant information, that is, to guarantee a sufficient time delay between the detection of important events and the driver's subsequent proper reaction. In other words, it can be stated that only vision provides information useful in the anticipation of future situations. Audition, on the other hand, plays a very modest role for anticipating future events, because it is limited to the near surroundings only. Furthermore, only a limited part of traffic re-

levant and anticipatory information can be related to hearing at all. Therefore, senses other than vision contribute, quantitatively as well as qualitatively very little to correct driving. They are also related mainly to past events (e.g., perceiving the traveling speed by the vibrations occurring due to proprioception or by hearing, e.g., the frequency of an auditory stimulus). All these and other reasons to be discussed in the following section support the primary role of vision in automobile control and justify its analysis as a proper correlate of information input and processing underlying steering operations.

If one is going to analyze the driver's eye movement behavior, he must know the essential characteristics of visual search as manifested by the patterns of fixations or the respective sequences. Therefore, chapter 2 is devoted to a consideration of the essential parameters of eye movement behavior under relatively static conditions. The term static condition refers to the stimulus (i.e., to its physical parameters like movement) and not to the perceiver. The perceiver in turn is cognitively highly active because he attempts to pick up further information and to develop his schema about the viewed stimulus configuration.

In the second chapter it will be pointed out that the

person's eye movement behavior depends not only on the subject variables but also on the task. Because of the interdependence between eye movement behavior and the subject's task, it is useful to describe the driver's task - this is the goal of the third chapter. Such a discussion is included so as to facilitate the understanding of eye movement behavior.

Subsequently, the general question arises as to whether it is reasonable to investigate foveal information input as a proper criterion for the underlying information intake and for its processing. Furthermore, the environmental conditions facilitating proper reliability for the analysis of the driver's eye movement must also be determined. These two major aspects are discussed in the fourth chapter.

The fifth chapter is devoted to the contemporary research and theory of the car driver's eye movement behavior. The visual search strategy will be discussed in relation to the path of driving, environmental conditions, the drivers' characteristics, as well as those of a limited number of the vehicle's elements. The sixth chapter is devoted to discussing the applicable implications which can be derived at the present stage of research from the analysis of eye movement behavior in driving.

### 3. HISTORICAL BACKGROUND

The subsequent discussion concerning the eye movement behavior of automobile drivers is based upon the results of research done during only a single decade. The appropriate experiments could be conducted only after MACKWORTH (1968) developed a suitable method for registering a person's fixations according to the principle of corneal reflection. In addition, further technical work was required for constructing suitable vs portable instruments needed in experimental research in field conditions.

The first study related to the driver's visual input in field conditions was carried out by GORDON (1966) who, however, was not able to analyze the driver's fixations directly at that time. He nevertheless used an indirect method which provided him with the data necessary to make important statements concerning the driver's visual input in relation to available impinging visual information and road characteristics. Several years later the first experimental analysis of the targets of fixation of the automobile driver was carried out by ROCKWELL and his coworkers at Ohio State University. Since then, the analysis of the car driver's eye movement behavior become an established procedure; nevertheless, even today only relatively few researchers are engaged in re-



search focusing on this important topic.

Because of the relatively short period of time that could be devoted for investigating the driver's visual input, not all important investigational goals have yet been achieved. They remain therefore a future research challenge. However, on the basis of recently completed research it is appropriate to formulate new goals and to develop an improved methodology to guarantee increased accuracy of recording eye movements, as well as reduced work in data reduction presently connected with evaluation of the results. Nevertheless, in the context of the short period of research on this topic, contemporary research and theory are impressive.

#### 4. SMALL GROUPS OF SUBJECTS CONSIDERED IN STUDIES ON THE DRIVERS' EYE MOVEMENT BEHAVIOR AND THE VALIDITY OF THE RESULTS

The analysis of car drivers' eye movement behavior requires considerable time and energy, because data evaluation can be forwarded semimanually only if the environmental parameters are considered. As a result, much work is required to evaluate

50 (in Europe) vs 60 (in the States) single frames for each second of the record of each driving session. As a consequence, one can analyze only the data collected from limited number of drivers if a study is to be completed within a reasonable period of time. Therefore, subjects evaluated in each study very rarely yields more than a maximum of 10 drivers.

When analyzing a car driver's eye movement behavior, there are a lot of data derived for each single subject, because the eye is fixated three times per second, on the average. When comparing this kind of experiment with those carried out in the laboratory in the investigation of other perceptual processes, it becomes obvious that research in the laboratory usually involves a greater number of participants (although rarely a representative sample of the general population). Furthermore, the amount of data derived for each subject is typically rather limited in laboratory experiments. This problem will not be treated further here, but by contrast it should be recognized that field investigations of the eye movements of drivers provide small samples that have been extensively studied.

It should also be noted that although the laboratory subject fulfills a prescribed task, his perceptual system is never engaged with its primary task, that is to survive

under actual conditions, e.g., driving. On the other hand, under field testing, the subjects must only drive, and are not required to carry out special task-related instructions. Thus, the perceptual system of the field subject functions in a natural manner. Therefore, data observed in field conditions probably reflect more accurately a subject's perceptual processes than data collected within a laboratory setting. However, experimental designs that can be realistically used under field conditions are never as perfect or sophisticated as those possible in the laboratory.

The above experimental considerations may result in a tendency to place more emphasis on the results of laboratory research and less on field research which usually is characterized by the previously described problems. Instead of attempting to justify the field approach theoretically, a more pragmatic point of view should be preferred. If the results of the single field experiments already carried out are valid then it is likely that no discrepancies among the different studies appear. Accordingly, the results produced by field observation of the driver's eye movement behavior while driving in several separate experiments are remarkably consistent. In general, there is a good correspondence between the independent field studies. This observation should be considered as a better argument for the validity of the present experi-

mental approach than any theoretical considerations. As a consequence, it is suggested that the experimental results to be subsequently presented are valid, despite the small number of subjects participating in each individual study.

Chapter 2

EYE MOVEMENT BEHAVIOR AND  
VISUAL INFORMATION INPUT

## 1. EYE MOVEMENT BEHAVIOR

The visual system is the most active modality which facilitates the perception of colors, forms, spatial extensions, etc, from rather great distances. The other sense organs are, on the contrary, limited to information input from near surroundings, such as hearing, or from proximity, such as touch.

The dynamics of the eye in the process of gathering visual information is mainly manifested by its rapid movements, which guide the eye toward a successive scanning of different targets in the environment. In actuality, the eye moves from one to another environmental element with a frequency of about 10000 times per hour.

The temporal course of the visual search strategy can be divided into two essential phases, i.e., states of the eye. The first of them is the rapid movement of the eye from one to another target. This rapid movement will subsequently be referred to as saccadic eye movement or as saccade.

The magnitude of the saccadic eye movement, which is expressed in arc degree, is denoted as the eye movement's amplitude.

The second phase of the eye corresponds with that temporal extension during which no saccadic eye movement occurs, meaning that the eye is in a relative stable state in relation

to an unmoved environmental target. This state is called eye fixation or fixation. The duration of the eye's fixated state is denoted as fixation time, which varies from 0.25s to 0.50s on the average, i.e., the saccade's mean frequency is approximately 2 to 4 movements per second. The specific target which is focused on during the eye's fixated state is termed the fixation point.

The temporal course of the oculomotor activity consists, therefore, of a succession of changes between the saccadically moved and the fixated states of the eye. These two phases of the eye, and their temporal course in relation to the environment, describe the essential variables manifested during the visual search strategy, and will be subsequently referred to as eye movement behavior.

When using the term "eye movements" in relation to visual perception, one does not only mean the saccadic movement of the eye but, importantly, the eye's fixations, during which the information is picked up. Therefore it is paradoxical to use a well defined term as "eye movements" when considering information input. Because of this discrepancy it is suggested that the broader term eye movement behavior be used to refer to both the fixated as well as to the moving state of the eye.

The present dichotomic distinction between saccades and fixations represents a simplification of the oculomotor activity actually occurring. For understanding the considerations at hand, however, no further differentiation is required. It should nevertheless be mentioned that a detailed review of the oculomotoric activity and its underlying neural mechanisms are given by DITCHBURN (1973) and by CARPENTER (1977).

#### 1.1. Essential parameter of eye movement behavior

The essential parameters which influence eye movement behavior are the characteristics of the optical array observed, the goal of viewing, and the peculiarities of the subject in connection with his long, as well as short, termed variables, such as previous knowledge as compared to moods. YARBUS (1967) pointed out that different pictures are viewed dissimilarly. Furthermore, when the same subject viewed the same painting repeatedly, his visual search strategy altered as a function of instructions received in advance, i.e., in relation to the goal of the observation. For example, if a subject has to estimate the age of the pictured persons he reacts differently than when he judges their socioeconomic circumstances



etc. Furthermore, interindividual differences can even be obtained when different subjects view the same optical array under identical conditions. Figure 1 represents the fixation sequences of three male students viewing the same picture. The only instruction given was to observe the presented picture until each subject had the impression that he saw it completely. The essential inter-individual variations were of four main types. First, different subjects fixated different points while using, secondly, different sequences of eye fixations. Thirdly, there was an interindividual variation related to the number of fixations carried out by the subjects, i.e., total viewing time. Finally, the total picture's area considered varied among the subjects. This means that the eye movement behavior depended upon the subjects characteristics. Also, intraindividual differences can be obtained when having the subject view the same optical array repeatedly (without giving him any instructions) or when either the subject's psychological or physical conditions have changed. For example, a car driver manifests a different eye movement behavior when he is under the influence of alcohol as compared to when he is sober (e.g., MORTIMER and JORGESON, 1972; BELT, 1969) or fatigued (KALUGER and SMITH, 1970).

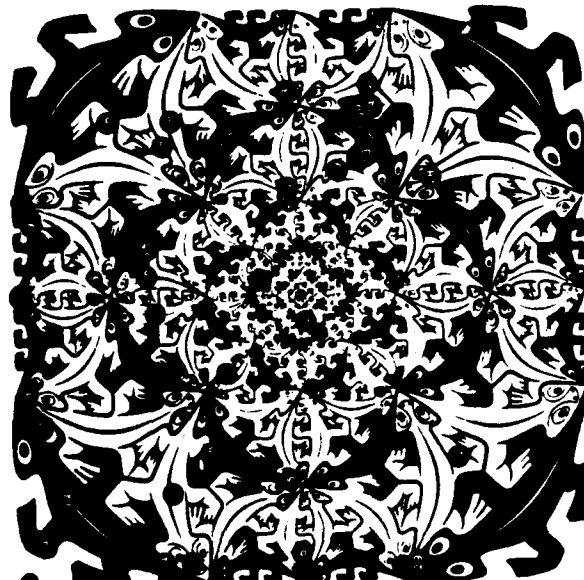
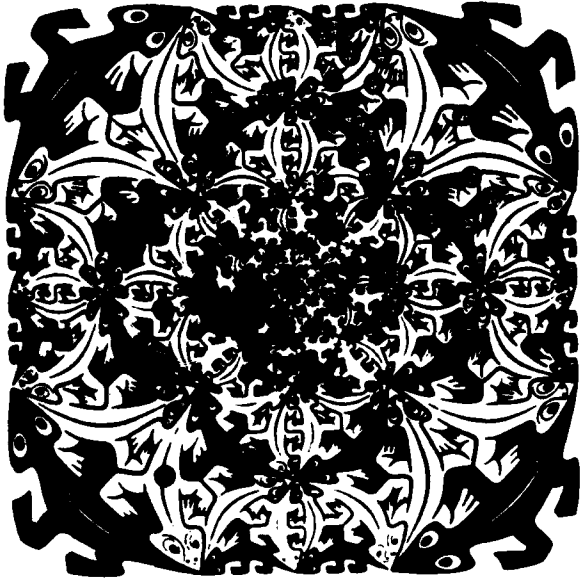
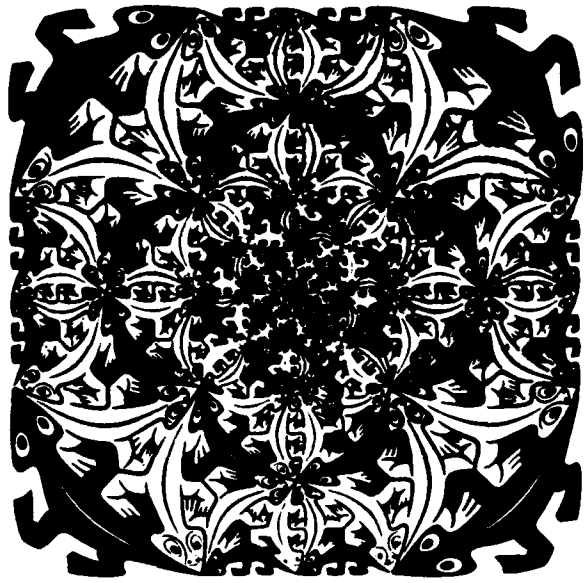


Figure 1: The sequence of eye fixations observed in three different subjects who were instructed only to observe the same picture of Escher, until they had the impression of seeing it completely. The interindividual differences are mainly manifested in the spots fixated, the total viewing time, the total number of fixations and their order, as well as the total picture area considered.

### 1.2. The reasons for moving the eye

At this point the question arises as to what are the reasons for moving the eye from one target to another, i.e., why the alternating sequence of saccades and subsequent fixations? The main reason for moving the eye is to fixate on different targets successively. This process is related to the physiological structure of the retina, as its different zones facilitate unequal visual acuities.

The specific retinal spot which corresponds to the maximal visual acuity possible is called the fovea centralis (see Fig. 2). Therefore, in order to see a target (under photopic conditions) most accurately, it must be brought into projection on the fovea centralis. This corresponds with changing the direction of sight, i.e., with altering the fixation point in connection with further oculomotoric processes such as convergence, accommodation, etc.

Figure 2 indicates that the relative visual acuity, which each retinal spot facilitates, depends on its angular distance from the fovea. The visual acuity decreases drastically with increased distance from the fovea. The relationship between the distance from the fovea, where a target is projected, and

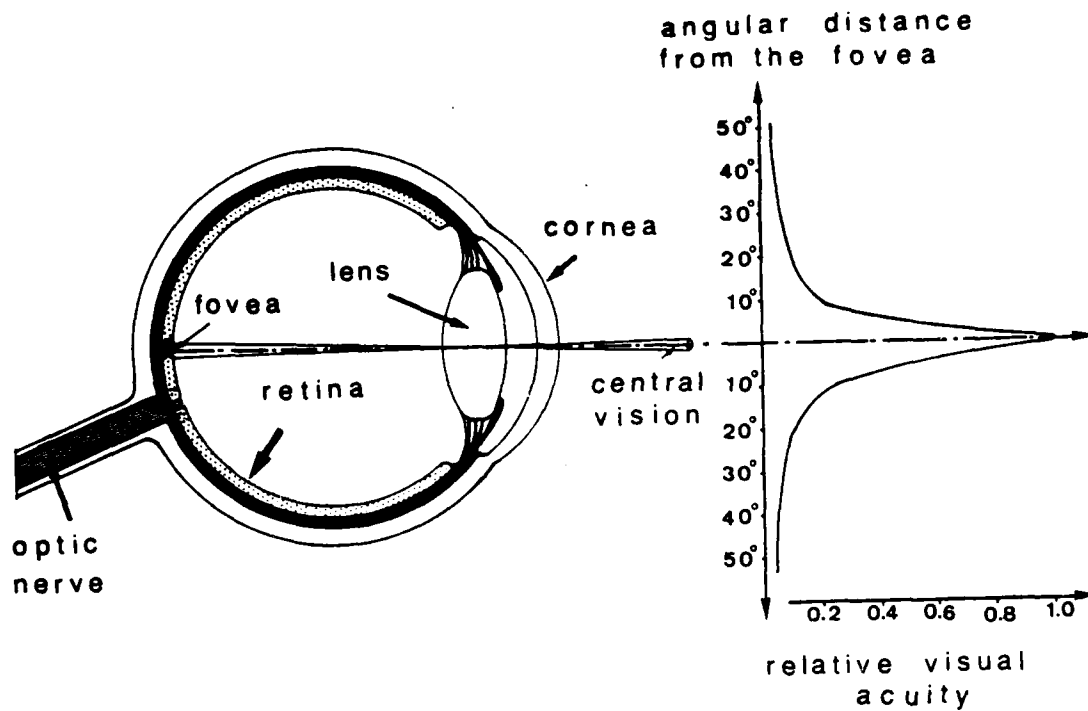


Figure 2: Schematic representation of the human eye (left) and the corresponding visual acuity as the function of angular distance from the fovea (right).

the respective visual acuity derives from four sets of conditions. First, the retina consists of two kinds of photoreceptors, whose total number is about 100 million (POLYAK, 1957). These are the cones and the rods, which permit photopic and scotopic vision, respectively. The retinal projection's texture can be compared to a mosaic because it is

composed of a number of photoreceptors of certain sizes. As to their size, the cones are thinner than the rods (see Fig. 3). Therefore, the maximal density of photoreceptors can be achieved by cones, rather than by rods. The quality of the retinal image depends, of course, on the density of the photoreceptors guaranteeing this process. The greater their density the better the resulting resolution. This fact favors a better visual acuity for such retinal regions which consist of a dense arrangement of cones only. This is actually the structure of the fovea. In its near surroundings there is still a great density of photoreceptors, i.e., cones and rods, which decrease with increased distance from the fovea. In far peripheral regions only rods exist, whose density is also low, resulting in decreased visual acuity when the projection's distance from the fovea is increased.

A second reason favoring foveal visual acuity over more distant retinal spots is related to the photoreceptors' neural connections with the optic nerve. As against the 100 million receptor cells, there are about one million fibres in the human optic nerve. This comparison leads to the estimation that on the average 100 receptor cells are connected to one single optic fibre (POLYAK, 1957). However, this ratio varies across the retina. The foveal cones are assumed to have direct,

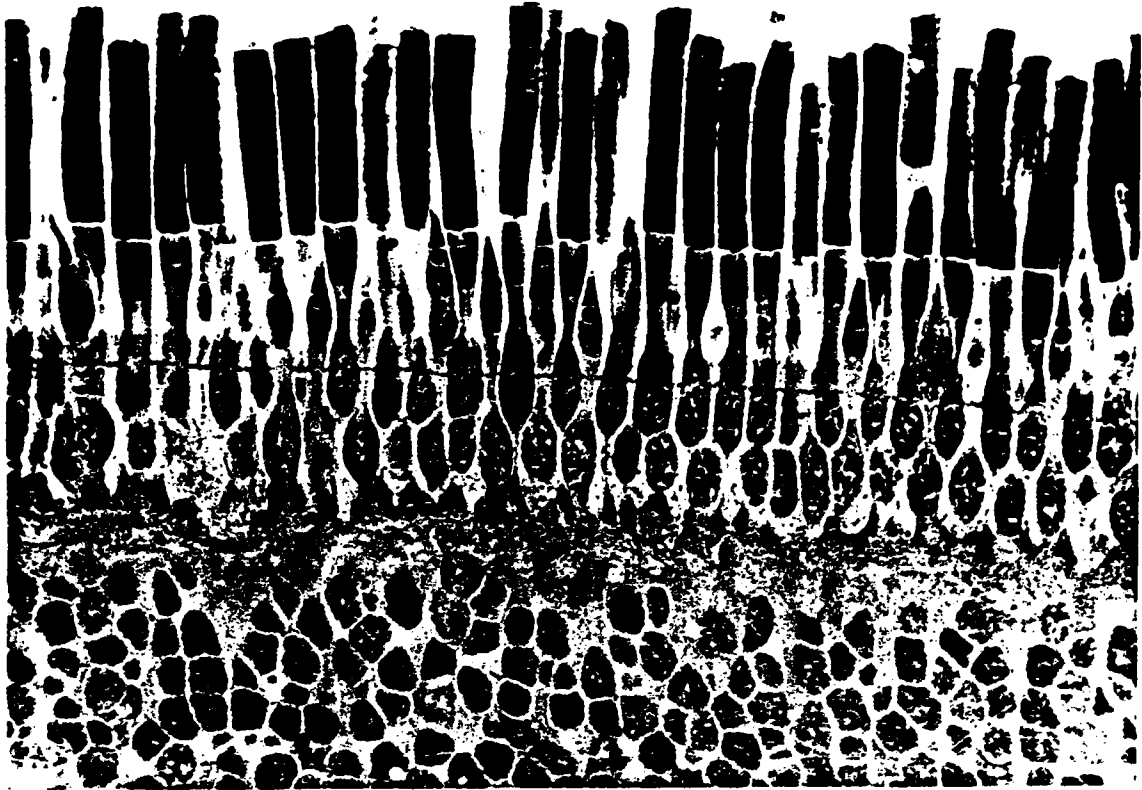


Figure 3: Electromicroscopic presentation of the frog's retina. The rods resemble black bars and the cones are triangle-shaped with small black points (acknowledgment to Dr. Charlotte Remé, who prepared this figure.)

single connections to the optic nerve. On the other hand, the ratio of the neural cell connections to the optic fibres increases with increased distance from the fovea. This means that the more peripheral a region is, the greater are the

number of receptor cells which are connected with a single optic fibre. GIBSON (1966) stated that "the greater the ratio of elements of the number of ingoing neurons, the less light is needed, but the greater the number of ingoing neurons, the more an image can be differentiated in various ways" (p. 181). Therefore, the unequal distribution of the neural connections of single receptor cells vs packages of them with the optic fibres, also favors a high foveal visual acuity.

A third reason for favoring the central (foveal) visual acuity is provided by the photoreceptor cell's orientation. This is optimal at the foveal region and becomes less favorable for decomposing the retinal projection with increased distance from the fovea.

The fourth main reason for the superiority of the fovea over peripheral regions of the retina is related to color vision. Color vision depends only upon the cones. Therefore, the ability to code color information ( i.e., in addition to other variables in the optical array) corresponds to the existing cones' density, which, as mentioned above, varies systematically across the retina. Therefore, this reason also favors the efficiency of information input through the fovea, as compared to more eccentric regions of the retina.

The fovea therefore facilitates the most detailed in-

formation input possible, especially since the efficiency of the four above-mentioned reasons is, in addition, cumulative. Because of the fovea's superiority for transmitting information, CARPENTER (1977) describes it as the retina's luxurious zone. The main reason for moving the eye is therefore to bring a target of special instantaneous interest rapidly into projection on the fovea. As a result, precise and rapid visual perception occurs.

High visual acuity is, for subsequent information processing, of rather great importance. FRANK (1978) stresses that if several stimuli, each containing an equal amount of information, are projected on different retinal regions which provide unequal visual acuities, then the transmitted information to the nerve fibres is proportional to each region's underlying resolution. The higher the facilitated visual acuity, the higher the amount of the transmitted information. FRANK (1978) emphasizes also that as to whether the transmitted information to the nerve fibres influences a subject's cognition depends on the situative constellation. However, that specific part of the transmitted information has a reduced chance to influence a subject's awareness which was previously suppressed by reduced visual acuity. This point of view stresses the pragmatic necessity to move the eye in such a way that a target of special instantaneous importance



will be projected on that specific retinal region, i.e., the fovea, which facilitates the highest visual acuity required to perceive a target in detail.

## 2. DISCREPANCIES BETWEEN THE OBJECTIVE COURSE OF INFORMATION INPUT AND THE INTROSPECTIVE PERCEPTION

The optical array is introspectively perceived as a spatial, as well as a temporal, continuity. Furthermore, one has the impression that every target can be seen in detail without regard to its environmental location in relation to the present fixation point. The following three aspects represent discrepancies between the course of objectively occurring information input and the corresponding introspective perception.

### 2.1. Spatial discontinuity

During each fixation only a limited part of the visual world can be seen, whose boundaries are determined by the field of view. The differences between monocular and binocular viewing conditions are only of a quantitative, but not of a qualitative nature. MACH has illustrated the boundaries of the monocular visual field quite impressively as shown in Figure 4.

The limitations of the visual field during every fixation of the eye are determined by its anatomical structure. Further-



Figure 4: The monocular field of vision as illustrated by MACH (from GIBSON, 1950).

more, the eyes' location within the skull also plays an important role, because, as Figure 4 indicates, external limitations like the nose or the eyebrows also influence the extension of the seen visual field. Despite these limitations leading to a segmental information input from the infinite visual world the environment is, nevertheless, perceived as a continuous extension.

## 2.2. Temporal discontinuity

The periodical changes between the moved and the fixated states of the eye are related to a temporal discontinuity in the input of visual information. For this reason, the course of the saccadic movement must be described briefly.

The saccadic eye movement can be characterized as a ballistic motion. It begins with a high acceleration until reaching a maximal velocity and then the eye reduces drastically the speed of movement in order to stop at the intended target of fixation. The time course of the saccadic movement, as plotted by CARPENTER (1977), is given in Figure 5 for different amplitudes. It can be seen that the time needed to complete a saccadic movement depends on its amplitude and can be rather accurately approximated by the following formula:

$$\underline{t} = 21 + 2\underline{A}$$

whereby  $\underline{t}$  is the time in ms needed to complete the saccade, and  $\underline{A}$  is the amplitude's magnitude in arc degrees.

The eye's maximal angular velocity during the saccadic movement is rather high. ALPERN (1972) mentioned, as an example, that the eye can reach a velocity of  $830^{\circ}/s$  when it is moved  $90^{\circ}$ .

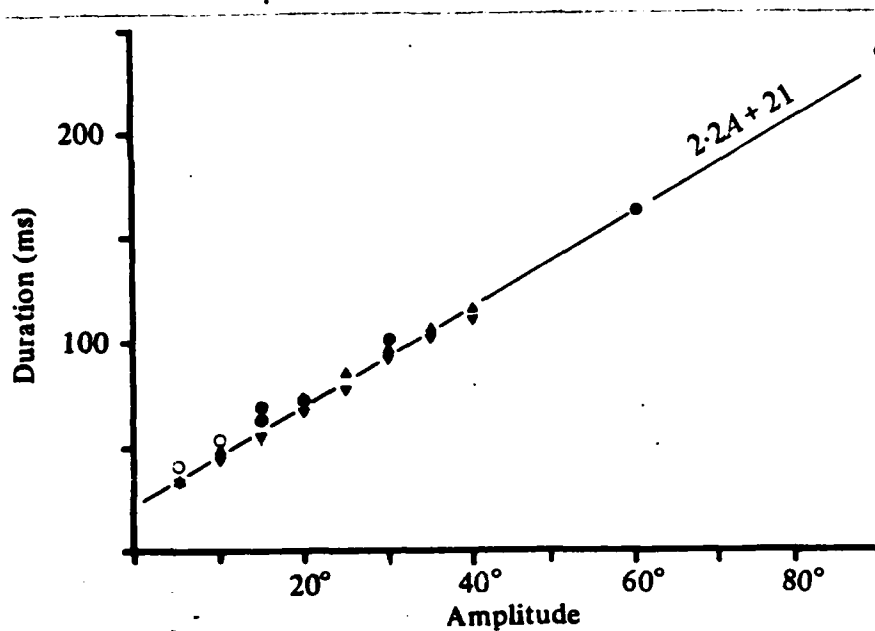


Figure 5: Duration of the saccadic eye movement as a function of its amplitude, according to data of ROBINSON (1964), YARBUS (1967) and HYDE (1959; from CARPENTER, 1977).

During the saccadic eye movement an increase of perceptual threshold occurs, i.e., saccadic suppression (e.g., VOLKMANN, 1962). Therefore, no detailed information input is possible during the saccadic movement. The saccadic suppression is caused by peripheral as well as central mechanisms (VOLKMANN, RIGGS, MOORE and WHITE; 1978). The peripheral mechanisms inhibiting information input are related to the rapid shift of the visual image across the photoreceptors, i.e., the smear

of the retinal image on the retina. This causes a reduced photomechanical effect on each single receptor. On the other hand, the central mechanisms governing the movement of the eye are related to a feed-forward loop. Simultaneously to the neural signal for executing the saccade, the visual input is also inhibited. There is therefore also a phase of a relative "black-out" during the saccade.

It is a simple matter to introspectively obtain a saccadic suppression. One can start by fixating his own eyes in a mirror. The eyes can subsequently be moved toward another point and vice versa. Despite any effort to observe one's own saccadic eye movements, they will not be seen, because they occur during the same time interval that the visual threshold is increased. There exists, on the other hand, no difficulty at all in observing another person's saccades.

These considerations indicate that information input does not occur continuously but alternately, i.e., during the fixations rather than during the saccadic movement of the eye. Nevertheless, an evident subjective impression that information input does occur continuously, contrary to what appears to be truly the case, does exist.

### 2.3. Visual acuity

The unequal visual acuity across the retina is a third source of the discrepancy between the actual course of information input and its introspective perception. Because different retinal regions correspond to systematically decreasing visual acuity with increased distance from the fovea, it is never possible during a fixation to perceive all objects located within the visual field in equal detail. Nevertheless, the subjective impression is that every object is seen continuously in detail, and without regard to where the eye is fixated.

A simple experiment can demonstrate that this subjective impression contradicts the actually occurring information input during each fixation. One can fixate his eyes in an arbitrarily chosen direction. Now, without changing the direction of sight, it can be noted that with increased angular distance from the point of fixation, vision becomes less and less accurate. This effect can be increased if another person moves a text through the visual field during that fixation. Its legibility decreases drastically with increased angular distance from the direction of fixation.

### 3. VISUAL ARRAY AND INFORMATION INPUT

The dependence of the eye movement behavior on the subject's variables was mentioned in a previous section. The visual search strategy, however, depends also on the characteristics of the visual array observed.

#### 3.1. Fixation point as an indicator for information input

The three above described discrepancies between the objective course of information input and the corresponding introspective perception pointed out that the visual world is perceived as a spatial as well as a temporal continuation, despite the fact that the underlying process is discontinuous.

At this point it is of importance to stress two facts which play a major role in future considerations. First, the information input occurs during the fixation, and not while the eye is saccadically moved. Second, the essential information input occurring during the fixation, which has the greatest possibility of being processed, originates from



the fovea rather than from the parafoveal, i.e., peripheral region of the retina. Peripheral vision also contributes to information input, but in a less detailed fashion.

However, the advantage of peripheral vision is that it facilitates information input from a rather great spatial extension in contrast to foveal vision, which corresponds with an angular extension amounting to approximately  $2^{\circ}$ . In the next section the general characteristics of the optical array will be described which attracts foveal vision, i.e., whereby essential information is picked up.

### 3.2. Optical array's characteristics and fixation points

Figure 6 shows a subject's sequence of eye fixations while observing freely a picture of Maurits Escher (see also Fig. 1). After the subject carried out these fixations he stated that he had completely perceived the presented picture. He could, however, have perceived in detail only the fixated spots within an extension of approximately  $2^{\circ}$  (the dot's size corresponds with this magnitude). Information from the pictures' remaining parts could have been picked up through peripheral vision, which does not facilitate detailed vision. This figure indicates that a rather limited rate of detailed information input facilitates, nevertheless, accurate perception. Because

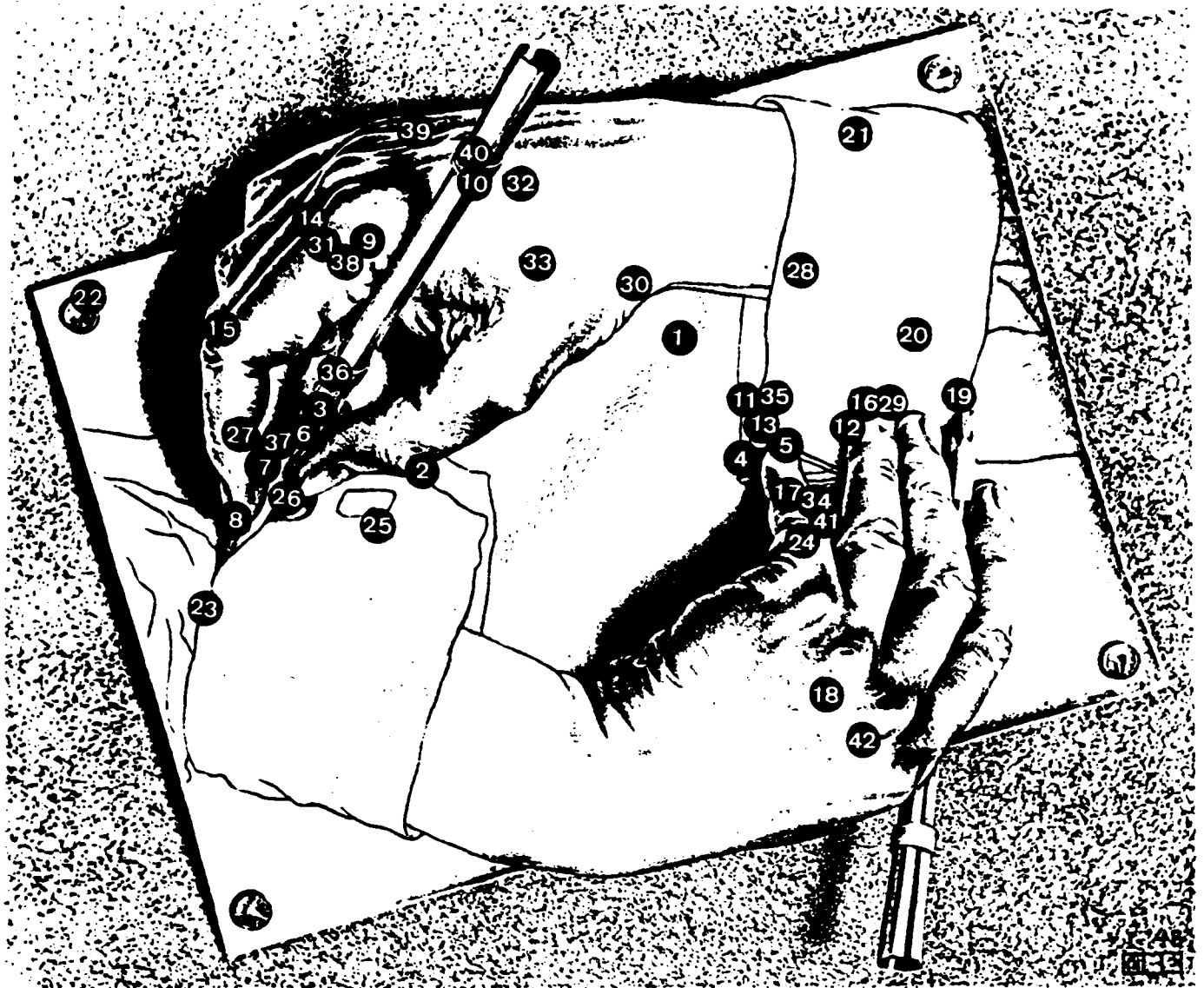


Figure 6: A subject's sequence of fixations while freely viewing a picture of ESCHER. The points of fixations are typically directed toward targets containing a relatively great amount of information.

only a limited part of the picture was fixated the general question arises as to whether the points of fixations have some common characteristics, or whether the fixations are distributed over the picture's area at random.

In general, as also indicated in Figure 6, the eye fixations are directed toward an optical array's characteristic spots. MACKWORTH and MORANDI (1967) pointed out that those parts of a picture attract the eye, i.e., are fixated, which are characterized by a relatively high amount of information. On the other hand, less informative parts are not fixated, or only seldom. This finding was confirmed also by ANTES (1974) or LOFTUS and MACKWORTH (1978).

The term "information", of an optical array's informative detail must be understood in a relative relationship, i.e., in comparison to its other parts. Thereby information can refer either to its cognitive aspects (prior knowledge or chunking strategies; i.e., MILLER, 1956) or to the abstract term derived from the information theory (e.g., ATTNEAVE, 1965). Actually, both of these aspects in their interdependence are the eye movement behavior's determinants. In general, a higher rate of eye fixations is directed toward targets possessing one or more of the following characteristics:

- 1) spots where an unexpected target is presumed to be located (YARBUS, 1967),
- 2) physical discontinuity of the optical array (ATTNEAVE, 1965) and
- 3) spots, which do not contain (from the point of view of the information theory) redundancy, e.g., irregular in contrast to regular geometric figures or, when considering the subject's cognition, spots which contain unexpected, as opposed to expected, elements like an elephant's body with a bird's head as compared to conventional representation (BERLYNE, 1958).

LOFTUS and MACKWORTH (1978) investigated the relationship between the subject's cognition and his pattern of eye fixations. They defined information in the following manner: A target's informativeness within a picture is higher, the lower its a priori probability of appearing within that context. LOFTUS and MACKWORTH (1978) operationalized this definition by using pairs of pictures showing different scenes like a farm or an underwater landscape. In this condition each element belonged to the same scene. In a second condition they exchanged one element, approximately the same size, between the pair of pictures. For example, in the second condition an octopus was placed in the farm (see Fig. 7) and a tractor with-

in the underwater scene. Therefore, the same element possessed a greater amount of information in the second as compared to the first condition. LOFTUS and MACKWORTH's (1978) results showed, as expected, that increasing an identical element's informativeness increased the probability of being fixated at least once, as well as being fixated earlier and for longer. Also, the mean fixation times increased as the target's informativeness increased.

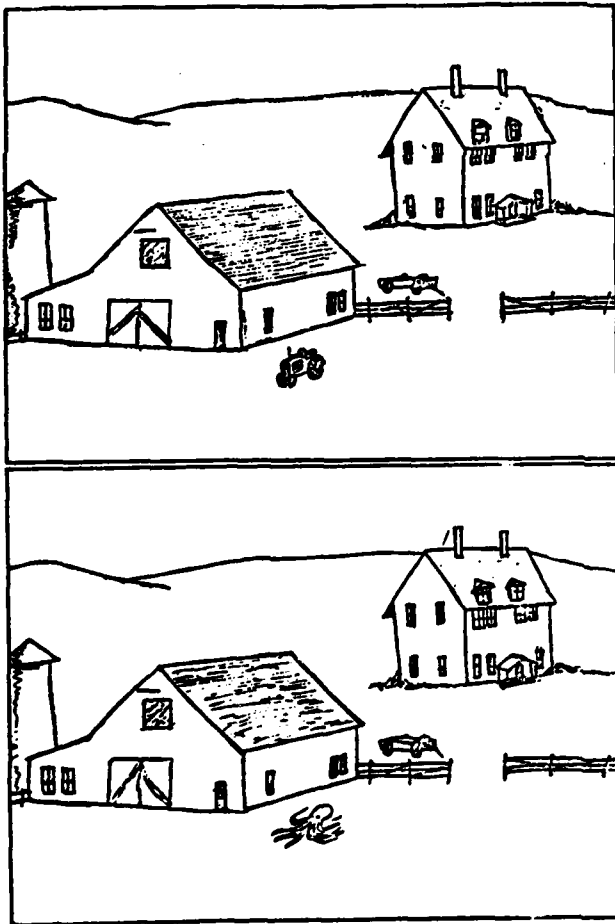


Figure 7:

A target's informativeness depends not only on its own characteristics but also on the context. For example, the tractor (top) is less informative than the octopus (bottom) because of the context (from LOFTUS and MACKWORTH, 1978).

### 3.3. The temporal course of the eye fixations

The temporal course of the eye fixation's succession while viewing pictures is a further indicator of the underlying psychological process. ANTES (1974) showed that the earliest (about three) fixations are directed toward targets which are relatively less informative than those of the subsequent fixations. Also, the mean duration of the earliest fixations is shorter and their average amplitude greater than those of the following fixations. ANTES (1974) concluded that the first fixations are devoted to general exploration of the optical array while subsequent fixations are devoted to detailed information input.

The dichotomic distinction between fixations for exploring vs processing, as ANTES (1974) suggested, should not be interpreted as a strict categorization. There is some evidence that in each fixation information for exploring, as well as for processing, is picked up (e.g., COHEN, 1977; COHEN and HIRSIG, 1978). Their respective parts may, however, vary between different fixations, and correspondingly emphasize one of the task's relative importance over the other one.

The listing of the rather static properties of the optical array which influence eye movement behavior is not complete,

because it does not consider sufficiently the dynamics of the the visual search strategy and that of the related information processing. YARBUS (1967), however, added to the list a further important notion. He stated that the next fixation of the eye is directed toward that specific target which contains or might contain information relative to the information presently picked up. NEISSER (1976) also supports this point of view in different words. He says that "each eye movement will be made as a consequence of information picked up, in anticipating more" (p.41). The aspect of dynamics in visual search strategy is of central importance for understanding the program governing the movements of the eye which is described in the following section.

#### 4. PROCESSES GOVERNING THE MOVEMENTS OF THE EYE

The points of fixation are not distributed across a viewed picture or, in general, across the optical array at random. On the contrary, they are directed toward targets characterized by certain aspects. On the other hand, during the saccadic movement an inhibition of visual information input occurs, so that it is hardly possible to assume that a fixation point is determined while the eye moves. Furthermore, the saccadic movement is of a ballistic nature. This is a further fact which does not support the idea that a subsequent target of fixation could have been selected during the saccade. This reasoning, i.e., that a specific target is fixated which is not selected during the saccade, must lead to the conclusion that each subsequent fixation point is determined before the eye begins to move. How does the mechanism function which guarantees an accurate program governing the movements of the eye?

The question raised above can be answered here in a rather simplified form excluding consideration of components other than visual or cognitive.

As to the visual component underlying the process governing the movements of the eye, it can be proved that visual information input occurs out of the whole visual field, i.e., through



the whole retina. The effectiveness of the information processed depends, however, on the corresponding visual acuity, as well as on further variables (e.g., MACKWORTH, 1976). Therefore during every fixation, i.e., while picking up information from the fixated target, other objects or events can be simultaneously detected due to peripheral vision, even when they are not necessarily associated with conscious perception. They provide, however, an undetailed detection of available targets. In this way, after each fixation, there are several targets within the visual field which are potential objects of the subsequent fixation. The undetailed information provided by peripheral vision about possible targets of fixations entails two conditions. First, the observer must know what the potential targets of a next fixation are, and secondly, where they are located.

Analysis of saccadic movement has shown that before the eye begins to move, it is already known in which direction and at what distance the intended subsequent fixation point lies. The saccadic movement guides the eye toward that target and stops quite exactly, if the amplitude is rather small. When carrying out saccades with great amplitudes, the intended target is not fixated exactly (e.g., PRABLANC, MASSE and ECHALLIER, 1978). The intended fixation point is then exactly reached due to a further small movement of the eye which is

called corrective saccadic eye movement. These two movements are different not only in their amplitudes but also in regard to their latencies. The saccade's latency is approximately 200 ms while that of the corrective saccadic eye movement amounts to about 50 ms. It is therefore assumed that the underlying processes of these two kinds of movements are different, at least in part. PÖPPEL (1974), for example, suggests that for programming the saccade the direction, as well as the distance must be precalculated. For programming the corrective saccadic eye movement, on the other hand, only the angular deviation but not the direction must be computed. This suggestion is supported by empirical observations showing that if the subject is presented with periodic alternations of a limited number of required points of fixation, i.e., if he becomes acquainted with the amplitude and direction of the prescribed saccades, then the latency of the saccade becomes shorter, even if the subject does not know in advance when the saccade should be carried out.

The above mentioned evidence suggests that the subsequent target of fixation is known before the eye begins to move, and that the required information could have been picked up from input through peripheral vision. The mechanism guiding the movements of the eye can therefore be characterized as a sensomotoric feed-forward program.

The principle of the feed-forward program is to facilitate a rapid flow of relevant information input. Therefore, this system can not function according to the characteristics of the optical array only, but in connection with the observer's cognition as well as his processing capacity. The process of controlling the movements of the eye should be understood as a closed loop process consisting of four essential components in its simplified form (see Fig. 8). This program starts to function after a retinal projection (1) has occurred. Then, predetermined nerve fibres facilitate the neural input's transmission (2) from the retinal photoreceptors to the brain. This transmitted information correlates to the original retinal projection (e.g., COWEY, 1979) but is different in its dimension, as the electromagnetic waves are now nerve pulses (spikes). Also, an abstraction of the available information already occurs at the retinal level, as LASHLEY (1941) pointed out. Furthermore, only a reduced part of the information available at the retinal level is transmitted to the visual cortex as a consequence of the greater number of the photoreceptors as compared to the number of the optic nerve fibres. GREGORY (1966) characterizes the retina rather accurately as the brain's first stage.

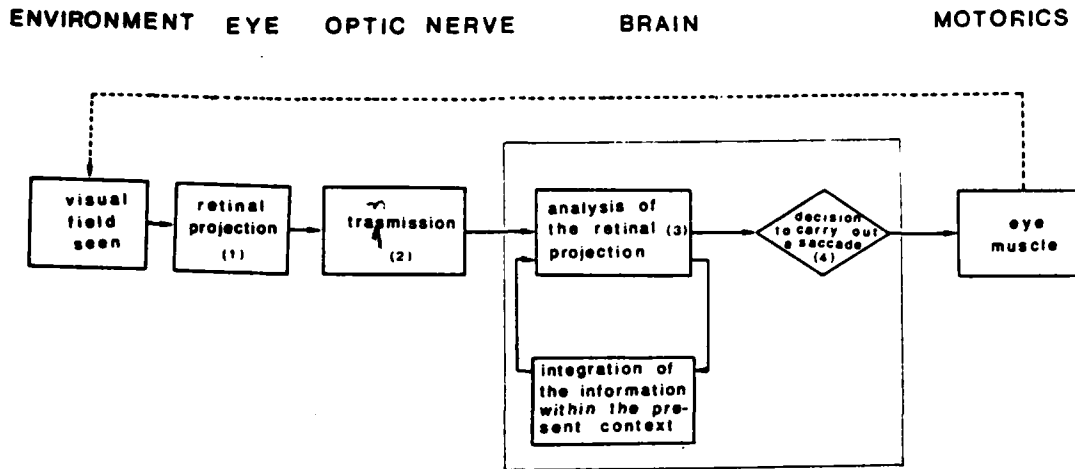


Figure 8: Schematic diagram showing the essential components of the program governing the movements of the eye.

The analysis of the retinal projection (3) occurs in the visual cortex during the ongoing fixation. This analysis, of course, does not occur for its own sake, but in relation to information already picked up, as well as that being sought, i.e., in dependence upon the subject's present cognitive schemata. The present information input is then integrated within the cognitive schemata while modifying it. At this stage, after the information input has been processed, the subject can determine which information he is seeking in order to gradually complete the goal of observation, i.e., what target should be next fixated. Afterwards, the neural signal can be directed to the oculomotoric system, in order to carry out a new,

aim oriented saccadic movement (4), in order to bring the next most important target, within the shortest time possible to projection on the fovea. As soon as the subsequent retinal projection is available the described process starts over again.

The rapid sequence of discrete fixations allows the perception of the visual world as a continuity despite the discrepancy between introspection and the objective course of information input. The inputted information and its processing and integration within the existing semantic context facilitates the perception of the environment, gradually adding to knowledge about it.

There are, however, also fixations which are not associated with visual information input but with staring (e.g., PURKINJE, 1825). They are, however, the exception to the rule in visually guided behavior.

## 5. ANALYSIS OF EYE MOVEMENT BEHAVIOR AND ITS APPLICABILITY

Eye movement behavior is obviously an observable peripheral mechanism which is, however, closely related to central processing mechanisms. The succession of fixation points can be used as an indicator for effective information input. Some examples should illustrate the applicability of this research method. However, many of the possible applications, like reading, flying etc. can not be considered within this framework. The car driver's eye movement behavior, on the other hand, is to be discussed in the following chapters.

### 5.1. Efficiency of visual displays in teaching

GUBA et al (1964) analyzed the eye movement behavior involved in viewing a T.V. lecture. They found that subjects tended to fixate the speaker's face even when the lecture's central object was shown at the same time. The designer of that lecture intended, of course, to present the object optimally, i.e., to transmit the maximal visual information possible. As the results showed, this intention was not fulfilled. GUBA et al (1964) concluded that the central object should be presented separately, when possible.

Other objects, especially those which are highly attractive, should never be presented at the same time in order to avoid undesirable shifts of visual attention.

The study of GUBA et al (1964) illustrates one of the main goals of the analysis of eye movement behavior. This goal is, in general, to evaluate the visual design of the environment, in order to facilitate optimal and rational information input. The possibilities of applying this method are many. It may begin like GUBA et al did, with checking the efficiency of different visual displays.

## 5.2. Visual communication

The widest field of applicability of the eye movement technique will certainly be the comparison between the artificial visual layout of the environment and the information a subject picks up. Such a comparison can be useful for analyzing the efficiency of the work done in order to facilitate the rational information input from the environment. The relevance of accurate and adequate information input is increased when a person has to act under a relatively great workload, i.e., when an efficient output is required within a short period of time after the information input has occurred.

By comparing the available information with that actually picked up it might be possible to find out how the environment's characteristics should be evaluated in order to facilitate the input of the intended information. An example taken from the roadway traffic should illustrate this notion. The eye fixations of a total of 14 subjects were recorded and analyzed, as shown in Figure 9, when approaching an urban intersection. While 7 subjects were acquainted with the experimental route, the others were not. No subject got any specific instructions. The goal of this experiment was to study whether the subjects would fixate a traffic sign indicating "attention - tram 30m" ahead. Immediately after crossing the intersection each subject was asked which traffic sign was the most recent one he noticed. None of them could name the sign at all. The records of eye fixations indicated that no subject fixated that sign.

The reason for the driver's ignoring of this sign is supposed to be the great information load existing straight ahead, as well as aside. The driver's high workload does not leave him any spare capacity for being able to pick up information lacking immediate traffic relevance. The clear consequence of this example is that desired visual communication is not possible when the subject is concerned with his primary task. As to the investigated traffic sign the only rational conclusion





Figure 9: A sequence of photos taken from the test car while crossing an intersection.

which includes the driver's sequence of eye fixations, indicating that the driver did not fixate the traffic sign "tram 30m" ahead.

is to remove it to another place, i.e., at a greater distance from the intersection, where the driver is less loaded with traffic relevant information.

### 5.3. Training efficient visual search strategy

A further possible field of application is related to training an effective task oriented visual search strategy. Experimental results showed that efficient visual input must have been learned. For example, there is a developmental trend (e.g., MACKWORTH and BRUNER, 1970) as well as perceptual learning (e.g., COHEN and STUDACH, 1977). It must therefore be possible to find out how to train an efficient visual search strategy in relation to the task's specific cognitive aspects. How such an attempt should be realized is, however, not yet known, and it remains a topic of future investigational goals (see HOSEMANN, 1979).

5.4. Eye movement behavior as an indicator for cognition  
as opposed to mental disorders

Further possibilities for applying the eye movement technique might be as follows: Preliminary research indicates that eye movement behavior is modified during childhood. With increased chronological age the subject's visual search strategy becomes more adjusted to the optical array observed. For example, children look at pictures differently than adults do. Children's eye movement behavior is characterized by a relatively small amplitude of the saccadic movement, as well as by a small visual area actually considered. They consider small details rather than the whole configuration presented. Also, the child's mean fixation time is prolonged, as compared to that of the adults (MACKWORTH and BRUNER, 1970). Because the child's perceptual system is assumed to be less developed than that of the adults, the variables mentioned can, presumably, be a useful criterion for indicating a subject's cognitive functions.

In the same line of reasoning there is some evidence that the total time needed to identify a most important object within an optical array, i.e., to fixate it first, might be associated with cognitive processes. LOFTUS and MACKWORTH (1978) found that informative details attract the subject's

visual attention. They pointed out that if an object's informativeness is increased, then the probability of fixating it earlier is also increased. On the other hand, HUNZIKER (1970) pointed out that a visual problem could be solved only by those subjects who fixated the four crucial elements of the optical array with their first four fixations. If the subject fixated other elements in his first four fixations, he was then not able to solve the problem presented. However, it is not yet known what kind of relationship exists between the subject's ability to solve a problem and his eye movement behavior. Further research is needed for determining a closer relationship between cognition and eye movement behavior, in order to advance its use for psychological differentiation or for prognostic reasons.

The suggestions above are also supported by TYLER (1969), who investigated the visual search strategy of aphasic patients. His results pointed out that motoric aphasia was associated at the session's beginning, for a short while, with normal visual exploration. Later, however, the subjects fatigued very quickly and their efforts were poorly sustained. "This resulted in an adequate but concrete, and not very imaginable performance" (TYLER, 1969, p. 108). The receptive aphasic patients, on the other hand, manifested a total absence of normal scanning activity. "There was no exploration

of the visual stimuli and no attempt was made to actively explore the visual presentation" (p.109). This defect in visual search activity suggests an interference with mental processes which are regularly associated with visual cognition.

TYLER's (1969) results suggest that a subject's visual search activity can indicate some mental disorders. Furthermore, it may be speculated that any progress made during a patient's therapy could be reflected in his eye movement behavior. As a consequence, changes observed in visual search strategy can be used for controlling the progress of previous efforts.

#### 5.5. Understanding another person's visual workload

The analysis of eye movement behavior can also be used for explaining, by visualization, a person's workload while performing a task. The realization of such a program can especially be useful whenever two different groups are in conflict with one another, e.g., because each group must be considered by the other. A conflict of this kind usually arises, for example, between car drivers and pedestrians.

Of course, there are drivers who sometimes prefer a challenge on the road in preference to a reasonable and rational controlling of their vehicles. On the other hand, pedestrians behave themselves similarly, from time to time, and risk their lives in doing so.

An improper pedestrian behavior is illustrated in Figure 10, consisting of a sequence of photos taken from a car with a frequency of approximately two pictures per second. It shows how three ladies are crossing the road within a curve without considering the traffic situation. Only one of them looks toward the oncoming car, but only at the last second, when any reaction would already be too late, if the driver had not anticipated the situation.

On the other hand, Figure 10 also illustrates the driver's workload, as indicated by his sequence of eye fixations. It is rather clearly shown that the driver cannot and therefore does not focus his visual attention on the pedestrians only, because he has to consider the complete picture of the traffic conditions.

The consequence of this example is that driver as well as pedestrians should mutually consider each other. Drivers must be aware and always consider the possibility of some sudden entering their path of driving, especially children and elderly



Figure 10: A sequence of photos indicating how three ladies cross the road within a curve and, on the other hand, a sequence of a driver's eye fixations while approaching them. This figure clearly indicates the driver's adequate visual search strategy and his rather great workload. This or similar figures might be helpful in pedestrian education, as a tool for illustrating the driver's task.

persons. On the other hand, the pedestrian who must also know that the driver is not able to focus all of his visual attention at him.

Under unfavorable conditions the driver may be overwhelmed with essential information to be processed. Because of his processing limitations, he must select a part of the information available and possibly even neglect other relevant information like an important traffic sign (see 5.2. in this chapter) or even the presence of a pedestrian near the road. Therefore, the pedestrian, who acts under a relatively small workload, has to consider the driver's abilities as well as his possibilities, in order to protect himself. With mutual understanding of the other group of traffic participant's limitations, which might be improved, e.g., by confronting the pedestrian (preferably in his childhood) with the driver's objective requirements and abilities, a better insight could be the result. Insight, in turn, may reduce aggression between different groups of traffic participants and thereby increase traffic safety. The driver, in turn, must of course respect the needs of the pedestrians also.

The reader should not confuse the example presented with an attempt to protect car drivers and to blame pedestrians only. Car drivers, who walk and cross the road sometimes be-



have similarly, but presumably they do so less frequently. (Empirical data are not available for validating this hypothesis.) The example discussed illustrates only a possible way to better understand the task - induced requirements which are associated with reducing one's expectations. This example can be transferred to different activities where visual input is a dominant precondition for being able to perform efficiently.

## 6. CONCLUSIONS

The general characteristics of eye movement behavior, i.e., saccadic movements and fixations of the eye, were briefly described. The essence of moving the eye is to bring a target of special momentary importance into projection on the fovea in the shortest time possible, because this tiny part of the retina facilitates the highest resolution possible. Essential information input occurs during the fixated state of the eye. The saccadic movement is accompanied by a threshold increase and, therefore, no accurate information input is possible during this phase.

The eye movement behavior is influenced by cognitive components and task specific requirements. Because of the dependence of visual search activity on the task performed, it is of importance to know at least a little of the task characteristics in order to understand the functional meaning of eye movement behavior.

The central issue to be considered in the following is the driver's visual search strategy. Therefore, the next chapter will briefly describe the driver's activity and integrate it to the man - machine - environment system.

Chapter 3

T H E   D R I V E R ' S   T A S K   R E Q U I R E M E N T S

## 1. VISION AND DRIVING

The previous chapter suggested a close relationship between a subject's cognitive task and his eye movement behavior (e.g., YARBUS, 1967). Even though this statement is derived from experiments carried out in the laboratory it is obviously also valid for field conditions, i.e., for driving a car.

In order to study the relation between the driver's task and his eye movement behavior, the visual search strategy of 8 subjects was analyzed when approaching an Y-formed intersection. Every run began immediately after the driver could see the intersection ahead and ended before it's entrance. Each subject drove once to the left and, the next time, to the right (see Fig. 11, left side). Due to this variation one can study the influence of the future directional path, i.e., the driver's predetermined task, on his present visual search strategy, as observed in the intersection zone. The drivers completed the experimental route within approximately 10 s, on the average.

The essential criterion for the data evaluation was the eye fixation's lateral distribution, along the experimental route and on the forward view. The road was arbitrarily divided into the following three lateral parts: left, middle and right, as indicated in Figure 11 (right side). The observed fixation's

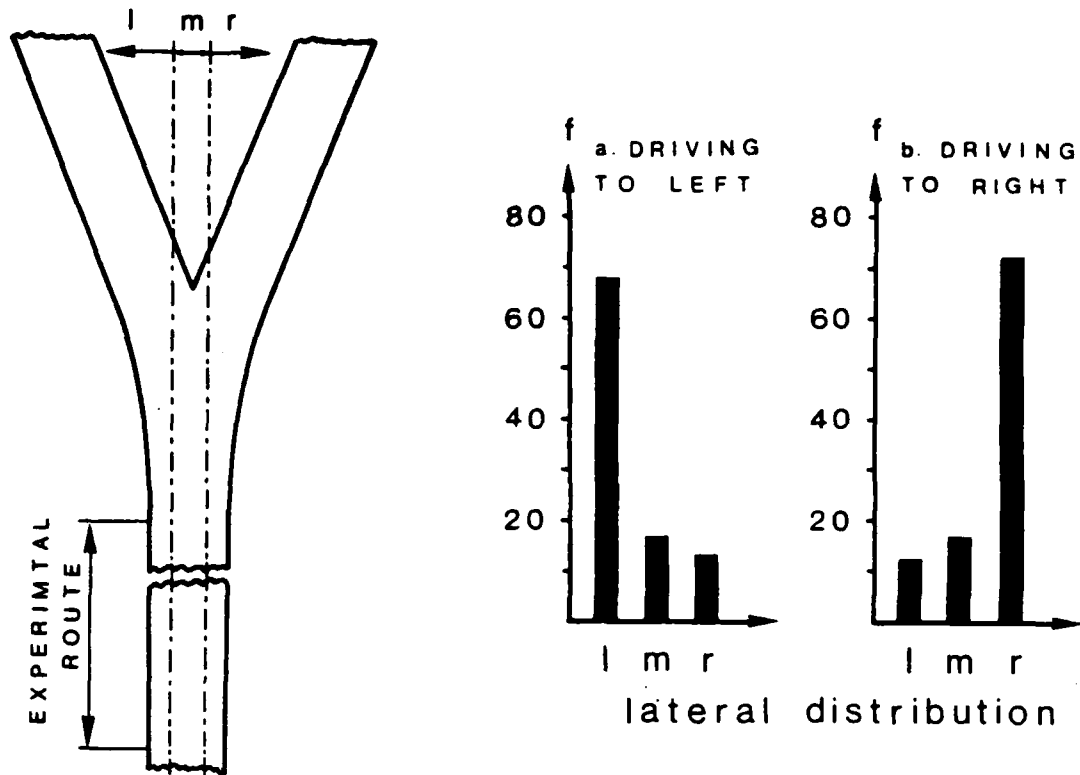


Figure 11: Schematic diagram showing the Y-formed intersection (biased scale) and the road's division into three lateral categories (left side of figure) and the drivers' eye fixations' lateral distribution (in absolute frequencies) while driving in the approaching zone preparing to drive either (A) to the left or (B) to the right (right side of figure).

lateral distribution is given in Figure 11. This figure clearly indicates a strong relationship between the driver's task (i.e., the direction where he subsequently has to drive) and his

visual search on the preceeding section of the road. This finding is also supported by COHEN and STUDACH (1977) who suggested that the change of the driver's eye movement behavior in the approaching zone (of a curve) reflect an anticipatory process. As will be discussed in another section, the future path of driving influences the driver's eye movement behavior because he is searching for information needed for guidance.

Adequate information input is an important precondition for being able to steer a car efficiently, i.e., to carry out the proper motor activities. The human factor is important for safe driving. FORBES (1972) has pointed out, that the majority of road accidents amountin up to 75 to 90 percent of all mishaps occur as a consequence of errors, lapses and the limitations of car drivers. Because of this, it is of importance to investigate those conditions which may decrease the frequency of accidents. One of these conditions is the driver's capability to process the information available in the environment in relation to its artificial visual layout.

Since adequate steering operations necessarily prescribe adequate information input, there must exist, as a consequence, an interdependence between the driver's operating the car and his visual search strategy. A further simple example should illustrate this statement. When the driver has to remain in one

place, e.g. when the traffic light is red, he then manifests a completely different pattern of eye fixations as compared to driving on open road or following another car. When not in motion, the driver visually explores his surroundings, i.e., he fixates targets which he would never do while driving. This pattern of "aimless" fixations is, however, interrupted from time to time for checking as to whether the traffic light is still red. While driving, on the other hand, the driver focuses his visual attention on the road and its near surroundings, i.e., for picking up traffic relevant information. He obviously directs his visual attention to his path of driving when he is under a great load of information to be processed. He, nevertheless, can also pick up information of general interest while driving, if he has the spare capacity.

Because of the strong relationship between the driver's task and his eye movement behavior, it is of advantage to consider the task requirements in order to better understand the visual search strategy.

## 2. TIME REQUIREMENTS IN DRIVING

The driver's "official" task can be described rather simply. The Swiss Traffic Regulations require, for example, that the driver must continuously be able to control his vehicle so that

he can fulfill all traffic regulations. To illustrate just one of the many unprecisely formulated requirements, traveling speed may be mentioned. The Swiss Traffic Regulations require that velocity should always be adjusted to the traffic circumstances, especially in regard to the vehicle's peculiarities and its freight, the road characteristics, and the traffic and visibility conditions. These formulations and similar ones are of course necessary to determine the responsibility for mishaps already occurred and for regulating the traffic flow, but not at all to define requirements in driving tasks. As a consequence, the driver has a rather great degree of freedom in operating his vehicle. He has to obey the traffic regulations of course, but on the other hand, he also has to act as a self-regulating system, i.e. to determine the best reactions for each event, and to carry it out at the right time while he continuously maintains his search for new events.

## 2.1. Driving as a purposeful activity

Driving is a purposeful activity. The basic purpose of the highway system as a whole, as FORBES (1972) has written, is to move people and goods efficiently and safely. This requirement includes two contradictory elements, because efficiency also means that the transportation should be carried out within the



shortest time possible (when the distance remains constant). On the other hand, increased traveling velocity is related, in general, to an increased probability of collisions (KOHLER, 1977). Therefore the realization of the highway's basic requirement, i.e., of efficiency and safety is no problem at all for maximization of one of the two components but one of a conjunctive optimalization of both simultaneously. The conjunction of transport efficiency and safety represents the driver's goal of driving.

The driver's activity is initiated by his goals, which presumably also influence his performance. The driver operates a defined vehicle within a given environment, and there is an obvious interdependence among these variables. Therefore, the variables driver - vehicle - environment should be understood as the main components of one system. When one of the components is missing, then no transportation is possible.

### 3. THE SYSTEM DRIVER - VEHICLE - ENVIRONMENT

Each system can be described as a circuit, i.e., as a loop. The question arises as to whether the driver's steering operation is related rather to an open-loop circuit or if it falls better under a closed-loop control. RUSSEL (1976) character-

rizes an open-loop as a control operation implying that the motor operations are programmed centrally and that they do not depend on peripheral feedback. Closed-loop control, on the other hand, implies the occurrence of peripheral (i.e., afferent) information input as a precondition in the ongoing control of movement production.

For driving a car it seems that both kinds of circuit operations (open-loop as well as closed-loop) are of importance. The open-loop circuit should be understood in terms of long term perceptual learning. Through increased learning "the motor schema comes to contain all the generalized integrated parameters that are needed to generate an unique movement to each situation" (MARTENIUK, 1976). The required reaction must be initiated, even by a fractional information input (e.g., cue-theory, see KOLERS, 1968) and the whole program runs "automatically". The advantage of such automatized reaction schemas, which are of importance in emergency situations, is that less time is needed for carrying out adequate operations. However, the presumed occurrence of automatized reactions is rather rare in common traffic conditions. They are also undesirable, because a good and efficient driver is not characterized by his automatized reactions in emergency situations only, but by his ability to avoid those types of situations.

The system driver - vehicle - environment can be described

partly as a closed-loop and partly as an open-loop circuit. The driver's goal and his long term learning are related to an open-loop control. On the other hand, the information flow underlying the steering behavior is related to a closed-loop circuit (see Fig. 12).

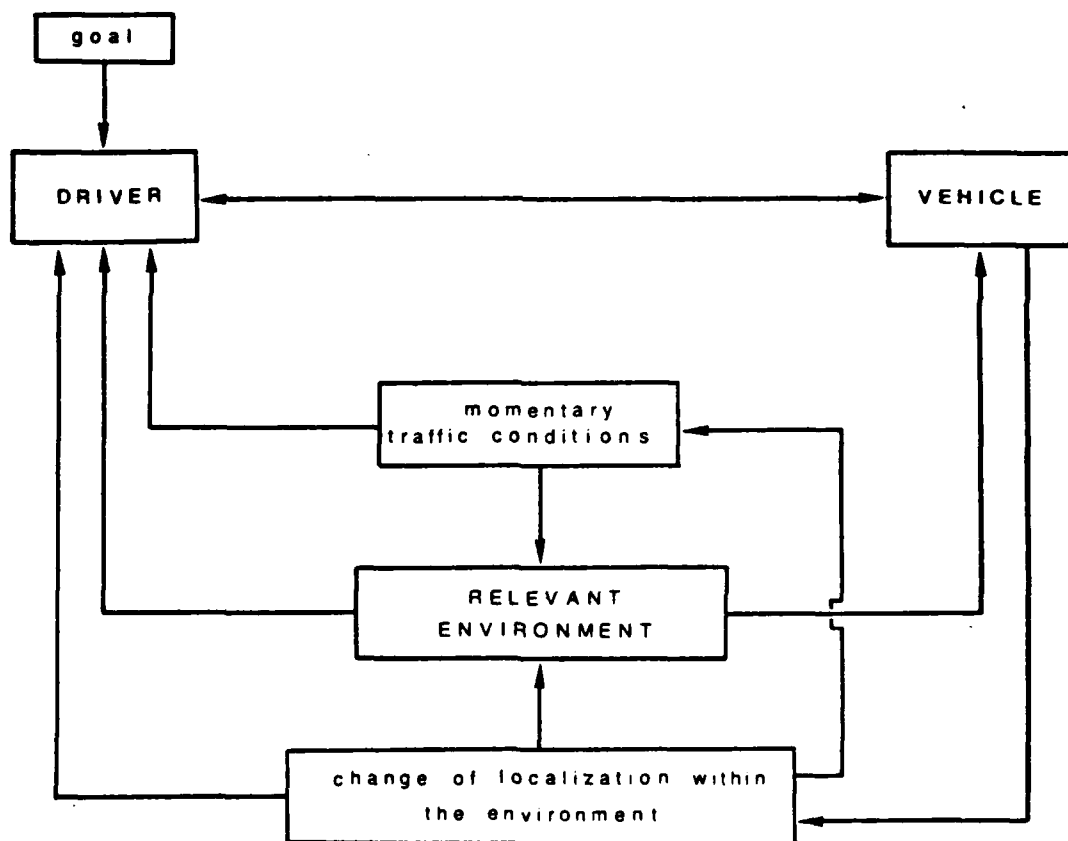


Figure 12: Schematic diagram showing the information flow underlying the driver - vehicle - environment system in a simplified form.

The driver influences the vehicle directly due to a limited number of operational elements such as gas pedal, breaks, steering wheel etc. In order to steer the car adequately he must pick up traffic-relevant information from the environment, which is mainly transmitted through visual modality. Although the environment can be viewed as a static displacement of pathways, buildings, trees etc., its importance must also depend on dynamic factors. These factors are, in general traffic conditions, as well as the driver's actual placement within the environment. The environment also directly influences the car through the route's characteristics (e.g., vibrations, friction, slope etc.) but also the driver through the information available to him.

On the other hand, the driver who operates his car according to his predetermined goal picks up information resulting from the car's movement parameters like noise, vibration (e.g., BUEB, 1977) or accelerations. Therefore, the car itself is also a source of feedback information. Similarly, the force needed for handling the operational elements, e.g., overcoming steering wheel resistance, provides further feedback information.

When traveling, it is self-evident that the car changes its location within the environment. The change of location is important information which indicates the car's movement para-

meters which the driver picks up visually as motion perception in the main, but also as longitudinal vs lateral accelerations. A further aspect of the altered location is related to the relevant environment the driver has to consider for picking up the traffic - relevant information. The part of the total environment presently relevant for driving is different from that which was of importance just a moment ago. The car's own movement also influences, on the other hand, the momentary traffic conditions, which is a further essential dependent variable to be mentioned here. The traffic conditions, including the driven route's characteristics, as well as other drivers' movements also depend therefore on one's own movement parameters. For example, time to negotiate an oncoming car, the place where it occurs and the maneuvers still possible depend partly, but directly, on one's own speed of traveling, e.g., the rate of changing one's own position within the environment. In general, the steering operations are initiated by the driver's predefined goal. While he is driving, on the other hand, he continuously picks up traffic relevant information mainly from the forward view and occasionally using the rear view mirror.

As a concluding remark, it should be recapitulated that there are four essential sources of relevant information input as indicated in Figure 12. These are the relevant environ-

ment, the vehicle, the rate of change within the environment and the traffic conditions as a function of time and of the own location. The synthesis by analysis (e.g., NEISSER, 1967) of all information picked up facilitates the driver's acting as a self-regulating system, i.e., always adjusting the car's movement parameters to the conditions of the moment. Through this adjustment the driver essentially fulfills the requirements of the Traffic Regulations.

### 3.1. The driver's subtasks

While operating a car, the driver has to fulfill his goal of traveling efficiently and continuously to adjust the vehicle's movement parameters to the environment's characteristics, as well as to the traffic conditions. Accordingly, McRUER, ALLEN, WEIR and KLEIN (1977) suggest a hierarchical task organization consisting of the three following subtasks:

- 1) Navigation, which is mainly related to determining vs choosing the path of driving which leads to the required destination, i.e., a spatial orientation within the network of roads,
- 2) Guidance, meaning that the driver plans his desired path of driving (for at least the next few seconds ahead) as well as the vehicle's movement parameters for each particular location ahead, and
- 3) Control, which is the requirement to check as to whether the

desired feed-forward plan is realized. If there is any deviation between the desired plan and its realization, then the driver has to minimize that difference, provided that in the meantime no event has forced him to change his feed-forward plan.

Navigation is, from the point of view of traffic safety, less important than guidance or control. Therefore, this subtask will not be mentioned further, except to say that it accounts for an increase in the driver's workload, e.g., when he travels through an unfamiliar city and must find a specific road.

The driver's continuous information input must simultaneously facilitate the fulfillment of the guidance and control subtasks. There is absolutely no possibility of neglecting one of the two subtasks in order to perform the other better. Nevertheless, the information input occurs during discrete fixations of the eye. When driving under a rather great load of information, peripheral vision might not be sufficient to facilitate adequate information input. The driver is then forced to direct his visual attention, i.e., points of fixations, to picking up information for either guidance or control. This process is obviously associated with time-sharing between the two subtasks. Therefore, the question arises as to how the driver

can fulfill both tasks simultaneously when the information input occurs successively. This question can not be answered completely at this time. It should be mentioned only that the information picked up is stored for a while in the iconic memory (e.g., NEISSER, 1967), facilitating its integration within the momentary schema which also remain stored in short-time memory for a further period.

Because the driver's reaction times are never shorter than the mean frequency of his saccadic eye movements, the suggestion that every motor activity depends rather on short-time memory functions than on present information input seems to be reasonable. Therefore, the necessity of fulfilling the two subtasks simultaneously is possible even though the respective information input occurs successively.

The subtask's duality of guidance, as compared to control, is associated with different processes which the driver has to carry out. Guidance is essentially associated with planning the future route of driving, i.e., to determine the desired path. This perceptual and cognitive activity is evidently a feed-forward program. The subtask control is partly a function of guidance, i.e., of the feed-forward program determining the desired path of driving. Control means that the driver checks as to whether there is any discrepancy between the actual and the



desired path of driving. If any difference exists, then he must reduce it to the smallest possible difference, provided that no relevant event has occurred in the meantime, to force him to change the feed-forward program established before. Consequently, control is obviously related to a feedback mechanism.

Basically, as DONGES (1978) suggests, the central idea of any driver model concept is the duality of the information available in the road's forward view. He has, however, used the term information for guidance and stabilization in referring to guidance and control respectively.

#### 4. INFORMATION INPUT AND MOVEMENT PRODUCTION

The subtask guidance connotes that the driver must pick up relevant information from the road ahead for setting up feed-forward programs. The longer the distance between the driver and the available information the better, presumably, would be the setting up of the feed-forward program. This corresponds to the time left for the planning and realizing of adequate performance in relation to the environmental and traffic conditions. The more time which is left, the more accurate the driver's reaction is assumed to be. This notion is supported by the fact that visual information must be coded and subsequently

integrated within the motor schema (e.g., SCHMIDT, 1976) as a precondition for adequate movement production, i.e., steering operations. MARTENIUK (1976) similarly suggests a two-stage process underlying motor behavior. He writes that "first, incoming sensory information is coded by an appropriately developed long-term integrated store that results in a temporary code being stored in motor short-term memory .... The second stage in the transformation process concerns the development of motor schema. Here, codes from motor short-term memory are seen as being integrated and abstracted to that final form of movement information is analogous to an intellectual process capable of producing a wide range of movements" (p. 185).

#### 4.1. Anticipation: Beyond the available information

The subtask guidance contains two essential aspects. First, as discussed above, the information input facilitates setting up feed-forward programs for future motor activity. Second, because the momentary conditions on the road are a matter of dynamic alternations, the driver has to mentally consider each possible development. The estimation of future events, however, reaches far beyond the information presently available. For example, a pedestrian or another driver is seen and the driver

and the driver must consider the possibility that they might suddenly enter his own path of driving in order to prepare his adequate reaction in advance.

At this point it must be stressed that the feed-forward program the driver is establishing according to the information he has already picked up is not a deterministic, but a flexible, one. The feed-forward program has to be flexible in order to facilitate needed change in it, as soon as a new relevant event is recognized. To be able to steer a car, even in situations where new events suddenly may occur, the driver is required to infer properly, cognitively, each future development from the available information. The cognitive extrapolation from the information already picked up for estimating future occurrences is essential in driving, and is termed anticipation. Therefore guidance, as a flexible feed-forward program should not consist only of the information available but also of its extrapolation for estimating possible events which might happen in the immediate future. Under this point of view the driving task can be compared to a continuous checking of hypotheses and their modification corresponding to on-going information input. During the course of time there is, however, a reduction in the amount of uncertainty in relation to hypotheses established in the past. In the meantime the driver sets up new hypotheses about future developments in the traffic situation, and thereby increases, once more, the uncertainty. This process

can be characterized in accordance with NEISSER (1976) as a cyclical one.

Anticipation might also have a direct influence on the driver's visual search strategy. In a previous section it was pointed out that a target to be fixated next might depend on the subject's present cognitive schema. As a consequence, the driver may also seek information in relation to his task vs his subtasks, and thereby anticipate where this information is located. That is to say that the driver may anticipate what information he is going to pick up in the next moment and where it is located.

#### 4.2. Control operations

The driver's control operations are obviously related to a closed-loop circuit, i.e., a feedback mechanism. In controlling, the driver always has to compare the car's actual state with the desired one and to correct any unwanted deviation greater than a certain limit of tolerance. The possible deviations are essentially related either to the car's spatial location or to its speed of traveling.

Four possible spatial deviations from a desired path of travel

ing are schematically shown in Figure 13. It illustrates two deviations in lateral directions (A and B) and two further ones in longitudinal directions (C and D), i.e., positional errors as compared to heading angle errors occurring while traveling on a straight road. After he recognizes the undesirable error, the driver has to readjust either the car's lateral position on the road or it's direction of travel. If the driver does not carry out the respective control operation he reduces traffic safety. In the case of lateral deviation there remain only small spatial tolerance limits outside his own driving path. On the other hand, a heading angle error would cause his leaving the road within a short time.

The essential visual feedback information needed to perceive a lateral deviation is located spatially at a different place from that needed to perceive a longitudinal error. For controlling the car's lateral position efficiently, the driver does his best if he fixates the road's borders at a close distance, provided that peripheral vision does not provide sufficient information. Longitudinal control, on the other hand, can be managed best if fixating the road's vanishing point while driving on straight roads. In curves, however, there is no constant point to refer to continually in the direction of driving, e.g., only an alternating motion parallax in lateral direction can be seen (see Fig. 18). (In modern roads the curves have no

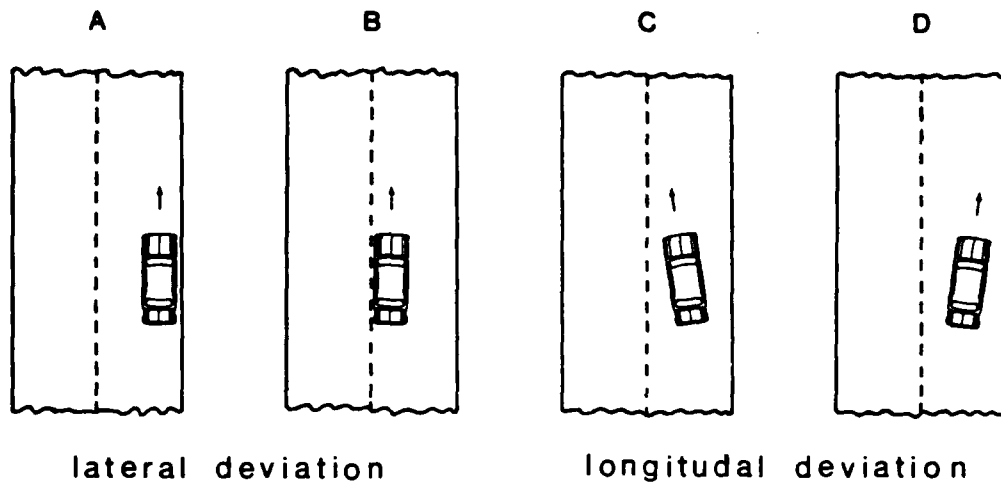


Figure 13: Schematic illustration of two positional deviations from the desired path of driving in lateral directions (A and B) as well as two heading angle errors in longitudinal directions (C and D).

radial structure but are designed as clothoids.) Nevertheless, it seems that the driver can most easily extract relevant information needed for longitudinal control from the farthest viewing distance available (e.g., COHEN and STUDACH, 1977).

## 5. CONCLUSIONS

The close relationship existing between the car driver's eye movement behavior and his actual task, i.e., setting up feed-forward programs, was pointed out. However, the driver's legal task is in general poorly defined (e.g., Swiss Traffic Regulations) and can be specified for particular situations only.

In general, the driver's task can not yet be completely defined because of the dynamics and the complexity of the changing environmental and traffic conditions. These circumstances require, on the other hand, a complex pattern of motor activity, cognitive judgements and perceptual processes. All of these are not deterministic in their nature but require rather an adaptive behavior. Essentially, driving should be understood as a dynamic system consisting of the three main components: driver - vehicle - environment. While steering a car, on the other hand, the driver has to fulfill three important subtasks in order to be able to drive safely and efficiently. These are navigation, guidance and control.

There is always a time delay between the perceptual process and the initiated motor activity. Well-planned activities are more desirable for safe and efficient driving than are mere

reactions to hazard. Therefore, the information the driver picks up must be related not only to a closed-loop circuit but also to an open-loop circuit. A part of these programs has to consist also of anticipation, that is to say a cognitive extrapolation from the previously picked up information needed for the estimation of any new event in the future.

At this point two essential preconditions are fulfilled in order to understand the driver's eye movement behavior. The first of them is the general characteristics of the visual search strategy as discussed in the first chapter. Because eye movement behavior depends also on what a person is doing, the second precondition is the driver's task, discussed above. Notwithstanding, the possibilities and the limitations involved in the analysis of the car driver's eye movement behavior should precede the review of contemporary research on this topic.



Chapter 4

VISION AND ANALYSIS OF EYE  
MOVEMENT BEHAVIOR IN DRIVING

## 1. THE IMPORTANCE OF VISUAL INPUT IN DRIVING

Information input and its adequate processing facilitates the establishment of anticipatory programs for future motoric activity and furthers the control of the car's present state. Both feed-forward and feed-backward mechanisms in driving depend mainly on visual information input. The major role of visual input for steering a car can be summarized in the three following statements:

- 1) Approximately 90 % of the total relevant information for driving is visual (HARTMAN, 1970; ROCKWELL, 1971; FISCHER, 1974; SHINAR et al, 1977).
- 2) Only through the visual modality is information input obtainable from a greater distance while all other modalities are limited either to a near distance (e.g., hearing) or to a proximity range. The major importance of distance, out of which the information can be picked up is that: The greater the distance between driver and a detected event, the more time is left him for planning his future activity. Presumably, the more time is left him, the more accurate and adequate his future activity will be, and
- 3) The visual modality makes possible inputting of the most

precise information about directions, distances, forms, velocities etc. The dominant role of these factors for steering a car need not be emphasized here.

The visual activity of a car driver is manifested in his eye movements behavior, which refers here mainly to the fixations and the saccadic movements of the eye. As the other kinds of the eye movements do not play a major role in information acquisition, they will be considered in special cases only. The central presuppositions for analyzing the eye movements behavior are the following:

- 1) Information input occurs during the fixations of the eye.  
Therefore, these fixation sequences might be attributed to flow of information processing or, on the other hand, repeated fixations on the same target could indicate that target's importance.
- 2) The target fixated represents a selection of available information. During its processing there occurs a further selection, i.e., reduction and abstraction in a higher level which remain, however, uncontrolled, and
- 3) During the saccading movement of the eye there is a drastic increase of the perceptual threshold, which inhibits the

information input during the eye jerks (VOLKMANN,1962). Nevertheless, the amplitude of the eye movement can be considered as an attribute of visual search strategy.

The analysis of eye movements behavior is limited in the direct study of peripheral mechanisms, i.e., information input. Central mechanisms, i.e., information processing, can not, thereby, be considered directly. Nevertheless, it is assumed that the peripheral mechanisms can be attributed to the central ones as is discussed in a later section. But what are the essential advantages and investigational goals of car drivers' eye movement behavior analysis?

One main advantage in investigating eye movement behavior is the fact that we can consider not only the available information in general but its particular parts, which a driver selects, as manifested by his pattern of fixation. In this manner a better approach is guaranteed in investigating the actual information input to the black-box-driver, whose reactions are principally measureable. Furthermore, in research on road safety, drivers' eye movement behavior can be registered in any real situation desired. These could be more representative situations for everyday traffic than is normally considered by, for example, accident analysis. Even though the central goal of

these kinds of experiments is to reduce the number of accidents, which are not representative but infrequently occurring events, the usual and not the extreme occurrence might be even of greater importance. In this connection von KLEBELSBERG's (1977) statement is of importance, i.e., that the central topic of the contemporary psychological approach toward driving is not limited to the analysis of accidents only. These accidents are only the irreversible result of a seldom constellation of circumstances and behavior reactions. Furthermore, an accident analysis does not indicate or predict whether the particular driver was normally able to steer his car safely or to predict his future behavior. Therefore, as von KLEBELSBERG (1977) emphasizes, the main objective of contemporary safety research primarily is the active prevention of accidents. The proper design for achieving this goal can more easily be derived from studies of representative traffic situations. This requirement can be suitably fulfilled by using the method of the eye movement technique.

#### 1.1. Investigational goals

The long-term investigational objective of studies on car

drivers' eye movement behavior is to find out some important cues about the optimal visual design of road surfaces and its near-by surroundings in order to facilitate rational information input. This problem consists (without considering vehicles construction) of the proper selection and arrangement of relevant road elements as well as of the drivers' capability to dynamically process the needed information. From the point of view of road safety the following aspects are central goals:

- 1) Which is the optimal arrangement of road elements on a specific route, especially those routes containing a great amount of information?
- 2) The question as to whether a driver's capability can be improved for dealing with a greater amount of information vs whether appropriate driver training programs can be developed for facilitating the driver's identification of most informative details, and
- 3) The possibility must be considered that a driver's eye movements behavior can be analyzed for prognostic purposes.

Despite the applied approach, eye movement analysis is of theoretical interest also. The dynamics of visual information acquisition can be studied not only in the laboratory but in

reality. While driving, the subject does not search for information because he was told to do so but he does it in order to survive. Thereby, not the artificial but the natural perceptual functioning can be investigated. Under these conditions one can study, e.g., how the information picked up in discrete "packages" (GAARDER, 1976) can be integrated into a subjective temporal and spatial continuous representation of the environment (e.g., GOULD, 1976).

## 2. ANALYSIS OF FOVEAL VISION: LIMITS AND POSSIBILITIES

While analyzing eye movement behavior, the targets of fixations are mainly considered. Nevertheless, the fovea is limited to a visual field of approximately  $2^{\circ}$  only, as compared to the peripheral vision, which covers an angular area of approximately  $160^{\circ}$ . Even though the relation between central and foveal vision amounts to ca. 1:10000, the fovea plays a major role in information acquisition. The main reasons are listed below:

- 1) Only a fixated target can be perceived in detail.
- 2) The fixated spot represents an attribute of visual attention. FESTINGER (1971) suggests that the eyes are moved also in order to jerk a target's image of momentaneous interest on to the fovea.
- 3) The fixations are devoted mainly to informative details but very seldom to redundant parts of an object observed (MACKWORTH and MORANDI, 1967; ANTES, 1974).
- 4) Between successive fixations of the eye, a causal relationship can be assumed (COHEN and HIRSIG, 1978) which might lead to the integration of information picked up in discrete



"packages" (GAARDER, 1975) in higher centers.

These considerations suggest that the momentary fixation of the eye as well as the focus of visual attention are always directed to identical targets (e.g., SCHOILDBORG, 1969). This assumption is supported also by YARBUS (1967) who states that the next eye fixation will be directed toward that particular target which contains or might contain relevant information in relation to a momentary cognitive context. These considerations propose also that eye movement behavior is a measurable attribute of irreversible cognitive activities at a higher level. Irreversibility refers to the fact that information already picked up changes the subject's cognitive schemata, i.e., that which was previously different. However, the irreversibility of the cognitive activities governing the process of information input and its adequate processing is limited by memory functions. Because a subject might forget what information he picked up during a preceeding fixation, he might re-fixate the same target after a period of time (e.g., GRONER, 1978).

### 2.1. Limitations of the eye movement behavior analysis

The analysis of eye movement behavior is, unfortunately, limited by some factors, which also should be considered, as they are important for understanding an observed pattern of fixations. The limiting, but not prohibiting, factors are as follows:

- 1) Fixating a target with the eye does not always correspond with seeing. Therefore, a fixation on an object should not necessarily indicate its perception. Fixation on a target is only pre-conditional for a detailed perception but no sufficient guarantee that that perception will occur.

THOMAS (1968) reports a car driver who actually fixated on a red traffic light but, nevertheless, continued driving on.

PURKINJE (1825) suggested in early times, that detailed information input must not necessarily occur in every fixation. An eye fixation in reference to information input may mean distinguishing between fixations devoted to exploring, processing, and staring which are respectively short, of about average, and long duration. Even though strict limits were never given, this statement has influenced recent research. If this statement is true, then the distri-

bution of durations must be represented at least by a bimodal vs trimodal curve.

For testing this hypothesis the durations of a total of 960 eye fixations, observed on six drivers while steering a car on a straight road, were analyzed as described elsewhere (COHEN and FISCHER, 1977). The mean duration was 0.36 sec. with a standard deviation of 0.22 and a skewness of 2.18; the respective distribution as well as the cumulative frequency are shown in Figure 14. This figure clearly indicates a unimodal curve. The observed distribution does not allow distinction between types of eye fixations by their durations only. Furthermore, about 70 % of the eye fixations might be approximated by a linear relationship between their cumulative frequency and the respective durations. These data suggest that duration of eye fixation alone is not a sufficient criterion for distinguishing among the three possible purposes of single eye fixations.

The duration of a fixation might also depend on the interactions among prior fixations, the amplitude of eye movements, characteristics of the fixated point, the present schema of the subject, as well as his capacity to process information. It might be assumed that detailed information

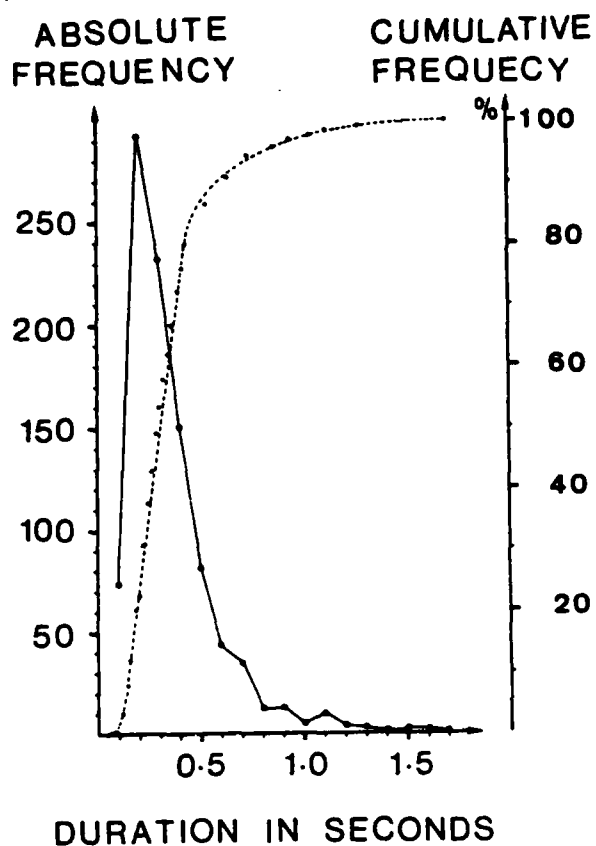


Figure 14:  
Distribution of 960  
fixations observed  
on six car drivers  
in absolute values  
(left axis) accord-  
ing to their dura-  
tions (solid line)  
and the respective  
cumulative frequen-  
cies (right axis).

is picked up through foveal vision, while parafoveal vision could be devoted simultaneously to exploration of further points of special interest in the environment to determine the next fixation point prior to beginning the eye move-  
ment. This dual function of the eye excludes also a strict distinction between eye fixations devoted only to process-  
ing or to scanning. Therefore, even though we can register

every fixated target, we must deal with uncertainty as to whether information input vs processing actually occurred. In contrast, we can always be sure that a non-fixated target could never have been seen in detail.

Therefore, two possibilities are given for the rational analysis of eye movement behavior. First, we are not interested in a single fixation but on the regularities of a visual search strategy. If a target or an element of the road is fixated repeatedly, then the accumulation of fixations indicates its importance. Second, we can consider visual search not only from a relatively static point of view, like their frequencies on defined objects, but we can also analyze a temporal sequence of fixations. Thereby, the sequence of fixations might be attributed to flow of information processed.

- 2) A second limitation in analyzing eye movement behavior results from the fact that the eye is functioning as a two-channel processor. Information is picked up simultaneously through foveal as well as through the uncontrolled extra foveal vision. Even though that peripheral vision does not permit detailed information input, this mode can be sufficient in very simple traffic conditions, as shown by BHISE and ROCKWELL (1971).

- 3) A third problem in understanding observed eye fixations is of a more theoretical nature. It is not yet known how the information picked up in natural situations in a sequence consisting of single fixations is integrated into a holistic representation. This fact can highly limit the phenomenological interpretation of observed fixations.
- 4) Two pragmatical considerations must also be mentioned. The first of them concerns the precision of the apparatus used to register the driver's eye movements, which could fluctuate approximately  $1^{\circ}$ . Furthermore, because of vibrations while driving, a readjustment could be required. The second problem is related to the expenditure of time needed to analyze the records. When using, for example, a Videorecorder, 3000 single frames must be considered if a period of only one minute's driving is analyzed. These facts lead to both using relatively few subjects in every experimental group as well as to a restraint upon the experimental routes.
- 5) Finally, a fifth factor which might negatively influence the validity of results observed on the car driver's eye movement behavior is the possible effect of the experimental situation on the subject, as well as on the apparatus

used. One can assume that the subject is a priori influenced due to the fact that his visual search strategy is the investigational objective (e.g., ROSENTHAL-effect; ROSENTHAL, 1963). On the other hand, the apparatus used (i.e., NAC Eye-Marc-Recorder) is adjusted to the subject's head and thereby might impair his viewing capabilities. If these two factors really influence the driver's eye movement behavior, one may then argue that the results observed do not reflect his natural eye movement behavior but an artifact. The consequence would then be that implications derived from the research would have no validity.

Unfortunately, it is not possible to provide exclusive evidence that the subject participating in such an experiment is not influenced by the two above listed factors. It cannot be known how a driver picks up visual information if his eye movement behavior is not registered and therefore no direct comparison to the experimental condition can be carried out. However, results of independent research, done while using different instrumentation are, comparable and essentially similar, e.g.: Eye-Marc-Recorder (COHEN and STUDACH, 1977) as compared to a television eye-movement system which includes the wearing of a helmet (SHINAR et al, 1977). Therefore, if there is any influence on the car

driver's eye movement behavior, it is at least not specific for the apparatus used. On the other hand, there is in contemporary research a rather good agreement between independent experimental results observed, which will be pointed out in the next chapter. These two facts support the idea that the experimental results reflect reality and are not an artifact.

A further argument against the validity of the experimental results could be that the subject participating in an experiment on vision in traffic is motivated to modulate his eye movement behavior in order to manifest a "good" visual search strategy. Even if such an exceptional case would occur, the driver still does not know where he should focus his attention, because he is not acquainted with the experimental goal. In any case, contemporary research is still not able to define what a "good" visual search strategy is.

Furthermore, when considering the driver's task, it can be stated that he is forced to pick up relevant information not because of the experimenter's instructions, but in order to survive, i.e., to avoid accidents. This necessity limits the driver's possibilities regarding any arbitrary and conscious alternating of well-established eye movement behavior during driving. If the driver has to act under



pressure of information to be processed as well as of the required motoric reactions, then he has essentially no chances to modulate his eye movement behavior. Any interfering cognitive activity would reduce the driver's performance and thereby increase the possibility of having an accident.

The above-mentioned reasons support the notion that the driver's eye movement behavior observed under experimental conditions does not represent an artifact. Further support can be derived from questionnaires (unpublished data) given to subjects during the years after each of them finished his experimental run (while using the NAC Eye-Marc-Recorder). The subjects stated that their visual search strategy was, during the experiment, equal or at least similar to what they were normally used to. Several subjects stated that they felt themselves disturbed by the Eye-Marc-Recorder, but that this was limited to the beginning of the experimental run and lasted approximately 10 minutes (experiments to be reported in next chapters never began before the driver completed a driving period of about a quarter of an hour). The conclusion that the driver does not modulate his eye movement behavior during experimental runs seems to be reasonable. The fact that a driver's visual search strategy remains stable when he is repeatedly driving on the same road (e.g., BHISE and ROCKWELL, 1971;

COHEN and HIRSIG, 1979) also supports the validity of the experimental results.

## 2.2. Conditions for reasonable analysis of the movement behavior

Now that general assumptions, advantages, as well as the limitations of eye movements behavior have been described, the conditions must now be discussed under which the applications of this research method is reasonable in studies related to information input vs processing. The first condition for reasonable use of this method is of rational information processing of the variable stimuli in contrary to, e.g., esthetic judgments.

In order to reduce the uncontrolled information input through the peripheral vision, the subject must be loaded with a great amount of information to be processed in a short time. In such a case it might be assumed that the relative importance of foveal, as compared to peripheral vision, should increase because the use of the fovea guarantees not only the most detailed but also the fastest information input possible. As a result of loading the processing capacity, the quota of

the uncontrolled information input should decrease.

The third condition for an efficient analysis is adequate spatial distinction between possible targets of fixations. These should also be of moderate size (see Fig.15).

When the conditions for a reasonable analysis of eye movement behavior are fulfilled, then it is at least theoretically possible to find out the relationship between the visual information input and the following motor activity needed for correct steering. If considering vision only, then an accumulation of fixations on specific road elements indicates its relative importance for driving. Furthermore, it is possible to consider the importance of these targets in dynamic relationships, i.e., as a function of path of driving, drivers' psycho-physical conditions etc. Consequently such a method enables one to find out the relationship between the available and the required information. Furthermore, all of these variables might be related to physically quantifiable measurements of the car itself such as the traveling speed, acceleration, steering wheel movements etc. (e.g., HELANDER, 1976; STUDACH, FISCHER and FRIEDINGER, in preparation). Therefore, the analysis of drivers' eye movements behavior facilitates a direct approach in the consideration of the most relevant variables in the closed-loop circuit of the road-driver-vehicle.

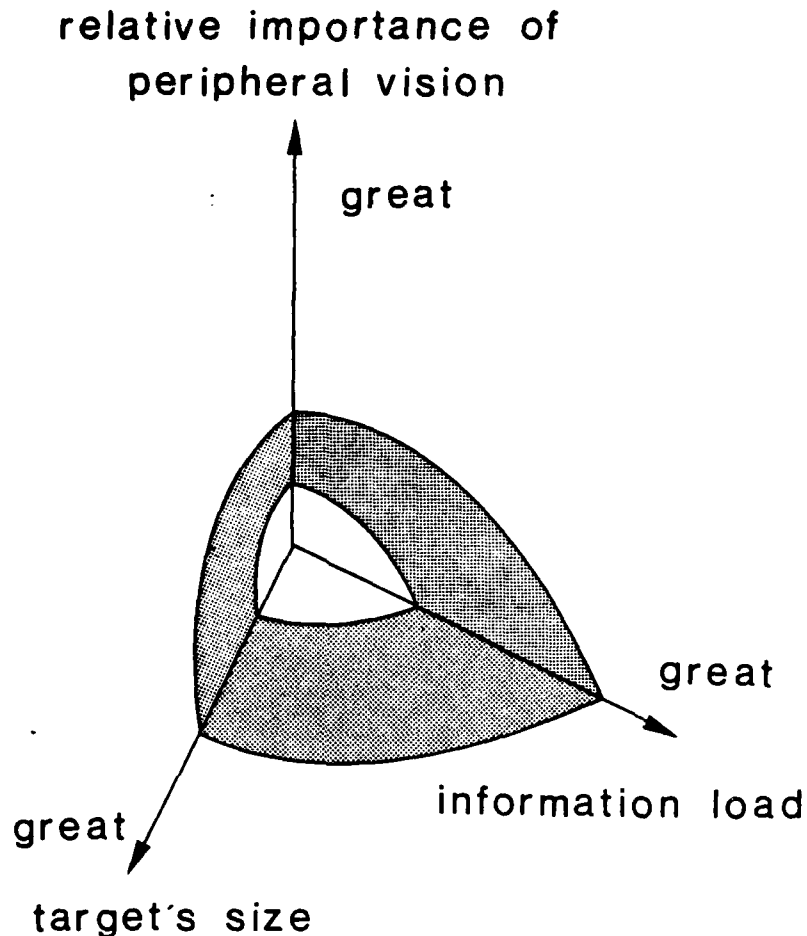


Figure 15: The essential conditions for the reasonable analysis of eye movement behavior in driving when rational information input is considered (modified after ROCKWELL and ZWAHLEN, 1977). (1) The relative importance of peripheral vision should be reduced in order of to avoid an uncontrolled information input through this region of the retina. On the other hand, to guarantee the sufficient programming of future eye movements, its importance should not be totally limited. (2) The information load must be quite large to avoid fixations on interfering targets. Nevertheless, this load of information must not exceed a subject's processing capacity. (3) As to a target's size, this target must be a relatively small and well defined one. In any case, the precision limits of the used registrat- ing apparatus must be considered.

Chapter 5

EYE MOVEMENT BEHAVIOR WHILE  
DRIVING

## 1. ON THE DRIVER'S VISUAL INPUT

When analyzing eye movement behavior, the target in fixation is assumed to be a possible source of information input. Some of the limitations of this analysis have already been mentioned, but a further aspect must be considered before the parameters of eye movement behavior in car drivers can be reviewed.

In most daily traffic situations, the driver's processing capacity is not totally loaded with relevant information. This assumption is supported by BHISE and ROCKWELL (1971) who showed that use of peripheral vision alone can enable a driver to steer a car under simple conditions. SAFFORD (1971, cit. in BHISE and ROCKWELL, 1971) stated that correct driving can be possible for a short while using only the information already stored, that is, without any current information input. This finding suggests that drivers can use this spare capacity to pick up information of general interest, e.g., to observe a pretty girl or presumably even to rest their eyes in order to avoid fatigue in the future.

These considerations suggests a "laziness hypothesis", that is, the individual degree to which a driver picks up relevant

information is a function of the amount of information the driver believes is sufficient for correct steering. When this subjective level of sufficient relevant information input is achieved (which can be influenced by temporal variables like emotional state), the driver might use his spare capacity for other interfering tasks of general interest (see Fig. 16). This interference should be, as far as possible, either avoided, to maintain a proper experimental design, or should be filtered if only the relevant information input is to be investigated.

The analysis of eye movement behavior should be considered within the framework of the closed-loop circuit of the driver - vehicle - environment. The factor of the driver is thereby a self regulating system. Because he can only use the given road for steering the car, the parameter of the path of driving will be considered first and then the variable driver will be discussed. Finally, research data on the characteristics of the vehicle will be presented. The role of peripheral vision should be discussed at the end of this chapter.

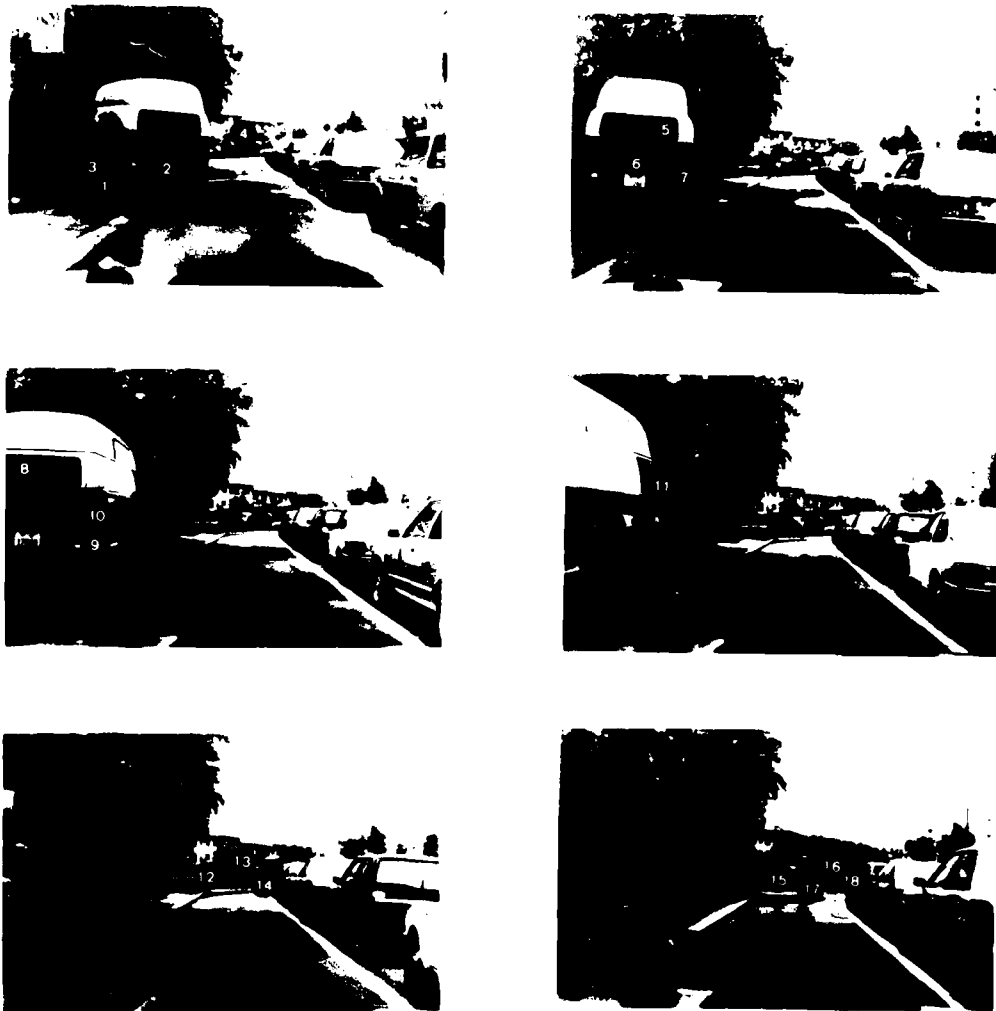


Figure 16: A driver's sequence of fixations observed while the lead-car drove on to the side walk. The subject spontaneously stated "who is that crazy driver" and later fixated that car's rear view mirror in order to see the other driver's face. This information input has little, if any, relevance for safe driving. (This sequence is the continuation of that presented in Fig. 24.)



## 2. PATH OF DRIVING

One central question concerns the identification of those elements of the road which carry the essential information necessary for driving. In this, both longitudinal and lateral vehicular status controls should be taken into account as well as the driver's practice of looking forward in order to detect actual occurrences or to search for potential events at a greater distance. GORDON (1966) studied this problem. He experimentally reduced the drivers' monocular visual field drastically either to  $4^{\circ}$  or to  $9.75^{\circ}$ . His subjects, who drove a car with a velocity of approximately 25 km/h on a curved two lane road, were permitted to see the environment only through a small tube. (All data are given in the metric system according to the international conventions. Original data given otherwise were transformed.) In this method, the visual input through the greatest part of the peripheral vision was excluded. GORDON (1966) concluded that the information picked up was derived mostly from only a very few elements of the road. These were principally the road edges and the center line. These categories fell into the permitted visual field in 99.0 % vs 96.4 % of observation times, when using, respectively, the large vs the small apparatus. Because the fovea enables a smaller extension than the used tubes, GORDON (1966) suggests that

these two categories of road elements were foveally fixated respectively for 85.7 % vs 80.9 % of total time. This result indicates that a relatively small number of targets carry the most relevant information needed in the proper steering of a car.

To study the visual search strategy under a great load of relevant information, a group of five subjects encountered in the experimental procedure an unexpected building site (COHEN, 1976). This site consisted of a crane which completely blocked the path of traveling. Therefore, the subjects had to drive to the side of the crane by using a small ramp that connected the road with the side walk (see Fig. 17). The obtained results indicate that the drivers were obviously most concerned with the input of relevant information and not with other tasks of general interest as indicated by the distribution of eye fixations. Most of the fixations were devoted to the small ramp, the road and the pavement and not to the big and "attractive" crane. In a control experiment, a further group of licensed drivers were presented with a slide showing the same building site, in which the ramp was overemphasized (COHEN, 1978). These participants, whose eye movements were recorded, were asked to observe the presented slide as if they had to drive there. This procedure notwithstanding, a completely different distribution of fixations was observed as compared to the real driving si-

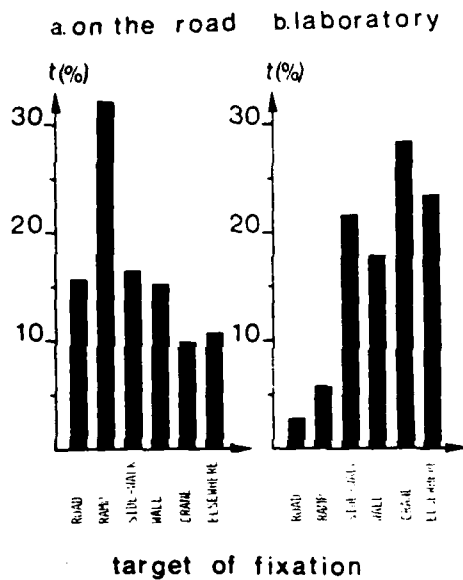
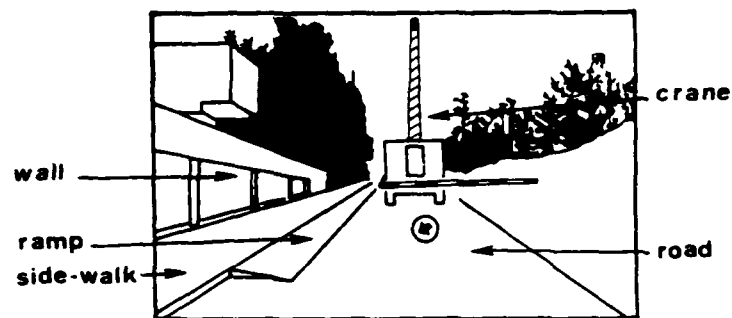


Figure 17: The building site which a group of subjects (N = 5) passed when driving a car and which another group of licensed subjects (N = 9) observed as a slide (of the real situation) in the laboratory.

The corresponding total fixation times in a percentage on well defined targets in both conditions is shown below.

tuation, as in the laboratory the crane was fixated very frequently (see Fig. 17). This finding indicates that a driver's eye movement behavior observed on the road can be attributed to a task oriented visual search strategy. This conclusion is in accordance with the findings presented above (see chapter 2). The lateral distribution of the targets which the driver fixated, while approaching a Y-formed intersection, were located at the same direction where they are going to drive on (see Fig. 11).

The subject's task depends also on the vehicle which he steers. MORTIMER and JORGESON (1975) compared the pattern of eye fixations of the same subjects when they operated either a motorcycle or a car. These authors pointed out that the mean fixation times are longer when operating a motorcycle than a car. The fixations are also located closer when riding on a motorcycle than driving a car. MORTIMER and JORGESON (1975) concluded that these differences reflect the manner in which the driver obtains visual information. The motorcyclists concentrate more than the car driver upon details of frictional characteristics of the pavement on which they are moving. This finding is therefore further support for the suggestion that the visual search strategy depends on the subject's specific task. This conclusion is, furthermore, supported by data regarding the influence of a road's characteristics as discussed in the next sections.

## 2.1. Curves vs straight road

The information available from a curved road is completely different from that obtained on straight roads. FRY (1968) suggests that the most precise directional information can be derived from the road's focus of expansion. Because the focus of expansion remains in an invariant relationship to the geometry of a straight road, it is therefore easier to perceive the future path of driving on straight roads than on curved sections.

When the driver is directing his fixations toward the focus of expansion, the preview time is maximized which is a further advantage for maintaining adequate steering operations. Also objects near to the focus of expansion appear to be stationary as against the rapid relative movement of other targets in the nearer distance (e.g., SHINAR, McDOWELL and ROCKWELL, 1977). Perceptually, therefore, the optical array in curves is of a completely different structure than that on straight roads. The objects do not appear to be stationary any more while driving around curves because they are close to the driver as his sight is limited to a relatively short distance, and this is part of an ongoing continuous alternation of targets' directional cues. In negotiating curves, in contrast to a straight route, no constant directional cue is given but a parallax of motion is seen (see Fig. 18). Accordingly, it is suggested that the visual



Figure 18a: A sequence of photos taken from a car while travelling on a straight road (i.e. approaching a curve). The motion parallax is mainly perceived in longitudinal direction.



Figure 18b: A sequence of photos taken from a car while travelling around a curve (i.e. that one seen in Fig 18a from a greater distance). The motion parallax is perceived in longitudinal as well as horizontal direction.

search strategy might depend on environmental variables (as well as on the sensomotoric activities that will simultaneously be carried out). The experimental results available justify this conclusion.

BLAAUW and RIEMERSMA (1975) investigated the driver's visual search strategy while driving on three different two-lane highway sections where no other vehicles were present. Two of these experimental routes curved to the left but had different radii, whereas the third route was a straight road section. The results indicated a dependency of the driver's visual search strategy on the particular experimental route. In essence there was a tendency toward increased visual search when driving around a curve as compared to a straight section. The intensity of the driver's search activity also depended on the curve's radius; the visual search activity was greater for the curve with the smaller radius.

BLAAUW and RIEMERSMA (1975) suggested that the driver picks up more information in curves than on straight roads. However, the experimental routes used in that study involved simple driving tasks so that the subjects had spare capacity and were even able to pick up relevant information from peripheral vision. The results showed approximately 30 % of all fixations evaluated were directed toward the sky. Therefore, it seems



that the results of BLAAUW and RIEMERSMA (1975) reflect only a part of the information input occurring in their experimental runs. Nevertheless, the relationship they found under conditions of low workload should be more readily observable under more complex environmental conditions.

SHINAR, McDOWELL and ROCKWELL (1977) studied the eye movements of car drivers on both the right and left curves of a two-lane hilly rural road. The experimental section of every curve was divided into 1) the curve itself, 2) the approach zone and 3) the straight road, from where the curve ahead could not have been seen. Furthermore, the authors differentiated between curves of similar physical properties that show different rates of accidents.

SHINAR, McDOWELL and ROCKWELL (1977) found a relationship between the lateral component of the eye movement amplitude and the characteristics of the driving path. MORTIMER and JORGESON (1972) found similarly that in right curves 59 % of total fixation was spent within a range of  $0^{\circ}$ - $5^{\circ}$  to the right of the direction straight ahead. In left curves, by contrast, 73 % of the total viewing time were in the range of  $0^{\circ}$ - $5^{\circ}$  on the road's left side. These findings are in agreement with those of COHEN and STUDACH (1977). In that experiment, similar observations were made on a small curved road

leading through a forest. The findings show that on both kinds of curves, which are, in general, of a mirrored symmetry, an asymmetrical pattern of eye fixations is observed. In a right curve most of driver's fixations are concentrated on the road's right side, but in a left curve, the fixations are distributed on the road's whole breadth. It was also determined that the horizontal component of the eye movement's amplitude was greater in a left than in a right curve in experienced drivers. In inexperienced drivers this variable varied, however, only at random (see Fig. 19). If assuming that the experienced drivers' eye movement behavior is more adequate than that of the inexperienced, as the qualitative judgement of the respective visual search strategy suggests, then this comparison indicated that eye movements behavior particularly depend on the observed peculiarities of the road and, in general, on the road's geometry. Because of these differences observed in experienced drivers, it is suggested that in both kinds of curves, a dissimilar strategy for information acquisition exists which, nevertheless, fulfill the same perceptual purposes.

The driver is mainly occupied with holding the vehicle on a preconceived path and, on the other hand, he must consider not only every change in the traffic situation but also be aware of every possible change. Furthermore, he has to adjust his speed and path of traveling according to the circumstances and

simultaneously plan his coming route.

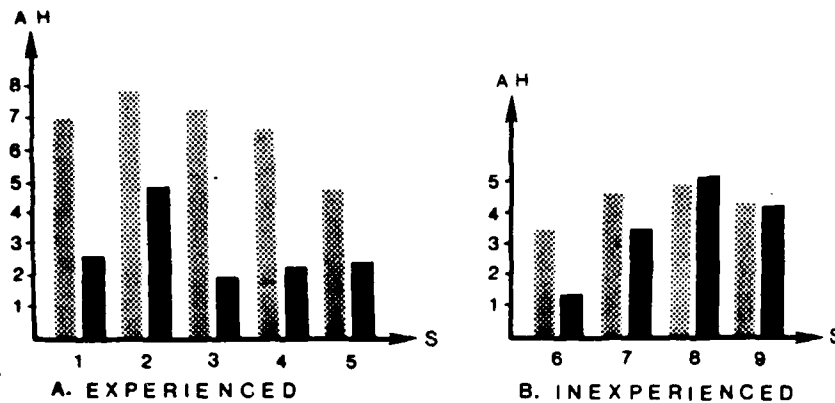


Figure 19: Mean amplitude of eye movements in horizontal direction (AH in arc degree) while driving through a curve to the left (dots) and a curve to the right (black).

The observed differences might be explained by distinguishing between two different functional kinds of information input while driving, i.e., control and guidance (see chapter 2). First, the driver must control the car's position on the lane, i.e., lateral control. The driver does that, presumably, by fixating either on the right or the left line of his traveling lane for short distances. The second functional meaning of an eye fixation could be spatial guidance, as well as the

anticipation of possible events which might be devoted also for longitudinal control. To this task a fixation is required that is located at the greatest distance possible. The greatest preview vision in a right curve is given when the driver fixates his eye at the greatest possible distance along the road's right side. In contrast, when driving around a left curve, the subject must fixate his eye along the path's left side in order to see as far ahead as possible (see Fig. 20). Therefore, the observed greater distribution of fixations in a curve to the left, as compared to a curve to the right, reflects a process of time sharing between fixations devoted mainly to the car's positional control, guidance and anticipation of future events. While driving in a curve to the right, both purposes can be fulfilled in the process of fixating targets to the right, e.g., either in near or far distance. Figure 21 illustrates an experienced driver's pattern of fixations while driving around a curve to the right and Figure 22 while he is driving around a curve to the left, i.e., the same curve traveled in opposite directions.

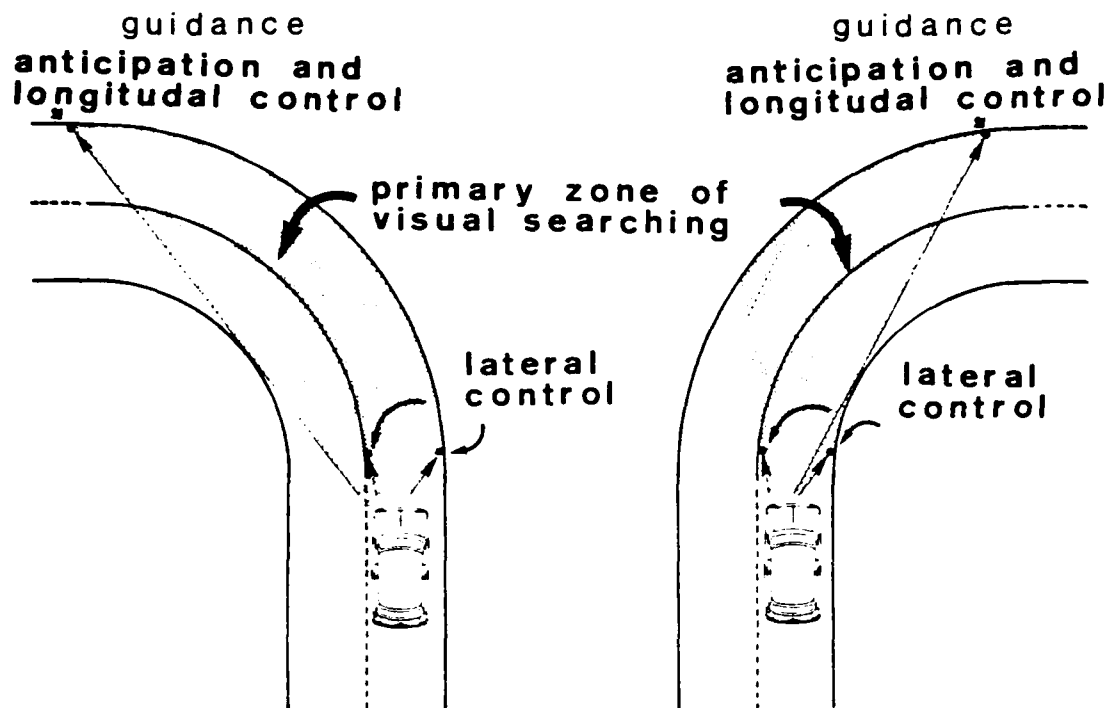


Figure 20: The schematic presentation of the primary zone of visual searching in a left and in a right curve. The angular distance of this effective zone is limited in every curve by the direction of fixations devoted mainly to guidance vs anticipation and longitudinal control and in those devoted mainly to lateral control. This angular distance is greater in a curve to the left than to the right. Therefore, because of the time sharing between functions, a greater amplitude of eye movements is evoked in a curve to the left than to the right.



Figure 21: An experienced driver's sequence of fixations while traveling around a curve to the right.



Figure 22: An experienced driver's sequence of fixations while traveling around a curve to the left (i.e. the same subject's fixations as shown in Fig. 21, as well as the same curve: driven in the opposite direction).

The considerations discussed above are supported also by the analysis of the vertical amplitude of eye movements (SHINAR, McDOWELL and ROCKWELL, 1977) as well as by that of fixation distances. In alternate order some fixations correspond with higher angular values (i.e., greater distance) followed by further ones corresponding with lower angular values (i.e., short distance) and so on. This sequence is in accordance with fixations devoted alternately mainly for lateral control vs anticipation and they are respectively located on objects in short and far distance as GORDON (1966) could point out by using more direct measures.

#### 2.1.1. Approaching curves

As some differences in the recording of eye movements behavior between a curve to the right and to the left have been pointed out, it might then be concluded that a change in a visual search pattern occurs when one enters a curve from a straight road. The question at this point is, then, whether the altered strategy of visual search might be attributed to an anticipatory process. This assumption is confirmed by two independent studies. Just before entering a right curve, a decrease of fixation times could be obtained as compared to



those observed on the previously traveled straight section (COHEN and STUDACH, 1977). This finding indicates an increased visual search activity. Furthermore, fixation locations, which were directed quite frequently toward the future path of driving, suggests that the driver picks up information from the coming curved path of traveling prior to its actual entrance (see Fig. 23).

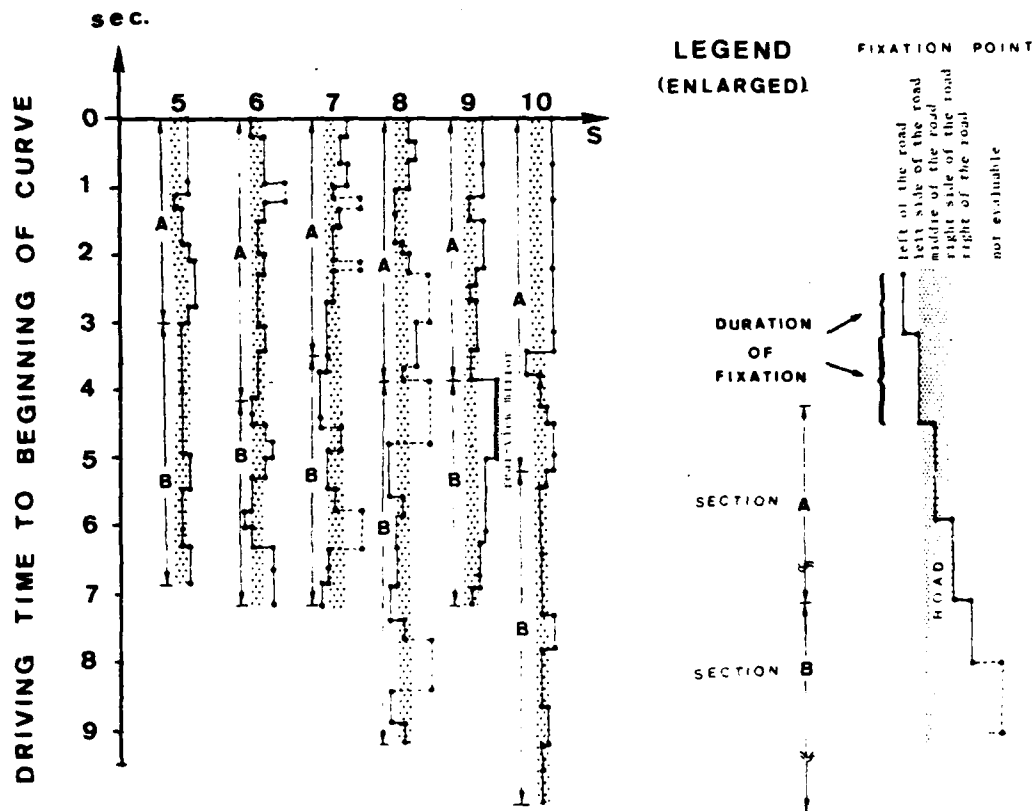


Figure 23: Duration and distribution of the eye fixations of every subject on the road and roadsides on Sections A and B while approaching a curve to the right.

On a two-lane rural road, increased visual activity can be observed as early as the approach zone, greater than on a straight road, and surprisingly, this activity is even more distinguishable than while driving in the curve itself (SHINAR, McDOWELL and ROCKWELL, 1977). This finding indicates clearly that the above discussed patterns of eye movement behavior in the two curve types is established through an anticipatory process occurring during the negotiation.

#### 2.1.2. Curvature

The findings on driving in curves vs approach zone driving support DILLING (1973), who stated that, from a perceptual point of view, the road's physical parameters do not describe a curve fully. He suggests that instead of dealing with the curve's characteristics only, one must also consider the distinguishing features of the approach zone. DILLING (1973) proposes using the term curvature for calculating the combined characteristics of the curve itself as well as its approach zone. This procedure might encompass more of an adequate perceptual definition. Also SHINAR (1977) pointed out that a road's curvature plays a major role in estimating the degree of the curve to come.

A section's curvature considered in relation to the frequency of occurring accidents, influences the mean fixation durations, as SHINAR, McDOWELL and ROCKWELL (1977) pointed out. The fixation times in curves with a frequent accident rate are longer (0.48 sec) than in accident-free curves (0.39 sec) with similar physical characteristics. The increase in fixation times is, furthermore, different in both types of curves. In a left curve the deviation of fixation times is greater in the approach zone than in the curve itself. The contrary is true in a curve to the right. This difference is noted by SHINAR, McDOWELL and ROCKWELL (1977) and they attribute it to the dissimilar viewing conditions of the road's right side in both types of curves. While the right shoulder of a left curve can be seen from a greater distance, the shoulder can be recognized in a right curve only in the curve itself. Therefore, the increased deviation is observed when the subject can anticipate the future path of driving in relation to the curvature. The increased deviation in fixation times, might, presumably, correspond with an increased visual search activity. This assumption is supported by the fact that experienced drivers tend to manifest a more uniform visual activity and to locate a greater part of their fixations as far ahead as possible for maximizing their preview time.

In summerizing the comparison between curved and straight sections, it is suggested that visual activity depends on the

characteristics of the path of driving, presumably because the driver needs, correspondingly, a different amount of information for the vehicle's control and its guidance. This amount should be greater in a curve than on a straight path of driving. The greater load of information in curves corresponds, presumably, with the accident rate as compared to that of straight roads (e.g., STUDACH, 1977). The driving risk especially increases when the road's curvature does not allow for an adequate input of information, i.e., leading to a discrepancy between the physical and the perceived curvature (e.g., SHINAR, 1977).

## 2.2. Intersections

Intersections are crucial elements in the road network. Conflicts between different road users who are traveling in different directions can arise even if only one driver does not respect the road regulations or when he does not adequately perceive the traffic conditions or a traffic sign (e.g., the cancellation of the priority of the road he is traveling on). The increased probability of being involved in a traffic conflict when crossing an intersection also corresponds to the increased rate of accidents occurring there.

The driver's eye movement behavior has not yet been investigated when driving across four-way intersections. The reason for this neglect of an important field of research has been the result of the inadequacy of the available apparatus for registering the driver's visual search strategy. Data evaluation is, however, then possible, only when the driver does not adequately search for relevant information (e.g., see Fig. 9; the driver did not check the traffic conditions to the right but looked straight ahead only). The reason for this is related to the driver's large eye movement amplitude which is frequently accompanied by fixations located beyond the field of registration. The experimentator is, therefore, not always able to determine the target on which a driver fixates. Furthermore, saccades with great amplitudes are accompanied by coordinated head movements which are rather rapid. As a consequence, the video-records done for simultaneously registering the environment are blurred (e.g., when using a NAC - Eye - Marc - Recorder) and the different targets remain unidentifiable. Nonetheless, these experimental limitations clearly indicate that the driver's input of information is increased when he is crossing a four-way intersection.

In the absence of data on the driver's eye movement behavior while crossing four-way intersections, his head movements can be used for indicating his search activity for relevant in-

formation. <sup>o</sup>ABERG and RUMAR (1975) suggested that head movements are a proper but rough indicator for measuring the driver's search activity. They pointed out that head movements are more frequent and have greater amplitudes while driving in a city as compared to rural driving. The rate of head movements increased when crossing an intersection as compared to driving on straight road sections. However, a different rate of head movements was observed for various intersections, as well as among different subjects. Even though this pilot study of <sup>o</sup>ABERG and RUMAR (1975) produced information on the driver's search activity, it did not indicate exactly what information a driver actually picks up. Therefore, the study of car driver's eye movement behavior while crossing four-way intersections remains an important field for future investigation, provided that appropriate methodologies can be developed.

### 3. ENVIRONMENTAL CONDITIONS

#### 3.1. Traffic conditions

The influence of traffic conditions on a driver's visual search activity has been only rarely investigated. Nevertheless, this influence can be considered from two general points of view which are either related to the driver variable or to the presence of other traffic participants.

##### 3.1.1. Car following

The traffic situation is partly determined by the presence of other drivers on the road. Within this frame, MOURANT and ROCKWELL (1970) studied the influence of a leading car on the follower's eye movement behavior. The subjects had to follow a car at a distance of approximately 25 m and with a traveling speed of 80 km/h. The results showed that a leading car did influence the following car driver's visual search strategy. It was apparent that the spatial distribution of the eye fixations is narrowed under car-following conditions, as compared to open road conditions, both in lateral, as well as longitudinal directions. A great portion of the fixations are concentrated just around the leading car or on it. As an example, on an open road 12.0 fixations per minute, on the average, are loca-



Figure 24: The driver's fixations are typically located on the lead car or about it. This search strategy is reasonable because the follower must react immediately when the lead car brakes, as occurred here.



ted on the car's own path of driving. When following a car, a mean of 76.7 fixations per minute is devoted either to the car's own path of driving or to the leading car. This result indicates clearly that the driver is highly aware of the leading car and because of this, he tends to neglect other targets (see Fig. 24). But, in contrast, the driver devotes more fixations to maintaining lateral control as manifested by 7.4 fixations in close proximity to the road's center line, instead of 4.3 fixations per minute on the average under open road conditions. In relation to the fixations which are devoted mainly to lateral control, there is simultaneously a decrease of anticipatory visual input as indicated by the decreased average fixation distance. Also, mean fixation time becomes longer (from 0.27 s to 0.31 s), and this might correspond to decreased visual search activity.

Car following, as compared to open road conditions, seems to cause a perceptual narrowing. Presumably, the driver intensively observes the lead car, because he must adjust his own activity within a short time to this leading car, especially when the lead car is breaking. With increased practice of following the same car, there is also a tendency to decrease his observation time, probably because the actions of the lead car are somewhat easier to predict. On the other hand, it is also possible that the follower can also rely on the leading car, e.g., such as in foggy weather to show him the advance path of driving. Both

Page 130 not available.

formation from other traffic-relevant targets for a shorter time when oncoming traffic is present as compared to the condition without oncoming vehicles as indicated in Table 1.

<u>target of fixation</u>	<u>with oncoming vehicle</u>	<u>without oncoming vehicle</u>
target of fixation	3.9	1.9
in left lane at opposing vehicle	42.5	-
in left lane not at opposing vehicle	3.2	10.1
center line	1.3	3.6
straight ahead in lane	32.5	50.1
right edge	4.5	9.7
off road to right	5.5	10.7
mirror	1.4	5.1
dash / interior	2.1	3.0
blinks / out of view	3.1	5.8

Table 1: Percentage of total fixation time with and without the presence of an oncoming vehicle averaged for motorcycle and car drivers (from MORTIMER and JORGESON, 1975).

The influence of the characteristics of the road (e.g., width of the road) on the shift of the attention toward the left in the presence of oncoming traffic has not yet been investigated. However, according to free observations of car drivers' eye movement behavior, it might be expected that the driver is

focusing on picking up relevant information from his own path of driving only, i.e., information for control, when he is traveling on a very narrow road. If there is sufficient lateral distance for safe passing of the oncoming vehicle, then the driver might attend increasingly to that oncoming vehicle. Further, when the road is rather wide or the lanes in the opposite directions are divided, then the driver might fixate on the oncoming vehicle only rarely. However, these hypotheses have not yet been empirically confirmed and therefore they should be considered rather tentative speculations based on observation of the records of the eye movement behavior of drivers.

### 3.2. Visibility and weather conditions

Visibility conditions crucially influence the available information input. Under conditions of fog, dusk, heavy rain or night-time driving, only a reduced input of relevant information is possible in comparison to the input under good atmospheric conditions while driving in the day-time. Presumably, this is an essential reason for the increased rate of collisions occurring during poor visibility conditions. Although atmospheric, as well as night-time conditions probably have a great influence on a driver's eye movement behavior, only a limited number of investigations have been devoted to such con-

siderations.

### 3.2.1. Night-time driving

MORTIMER and JORGESON (1974) investigated a driver's eye movement behavior during night-time, as compared to day-time, driving. They pointed out that during night-time driving the driver's mean fixation time is increased. Furthermore, his fixation points are increasingly concentrated on his own path of driving and for a shorter distance in comparison to day-time conditions. These findings mean that the rate of information input, as well as the driver's preview distance, are reduced under night-time driving conditions. Figure 25 represents one experienced driver's mean fixation times, as well as his mean amplitudes illustrating the changes occurring between day-time and night-time conditions while driving on the same road.

The role of the orientation of automobile headlamp beams is, from a pragmatic point of view, a central issue in the study of a driver's eye movement behavior under night-time conditions. It is particularly important to determine the specific headlamp beam configuration which maximally facilitates input of relevant visual information. The underlying assumption is that optimal information input occurs under ideal lighting condi-

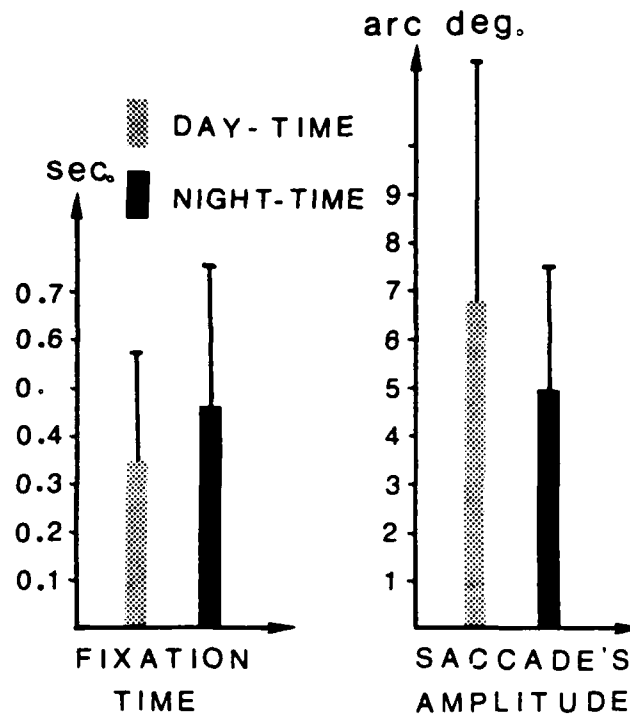


Figure 25: A driver's mean fixation times and the saccades' mean amplitude while traveling on the same road under day-time as well as night-time conditions.

tions (e.g., during day-time driving). Therefore, the particular headlamp beam configuration that produces similar input during night-time driving as that which occurs during day-time driving is to be preferred. That is to say, the requirement is to facilitate input of that particular information which the driver is seeking. On the other hand, this requirement is limited by the necessity of avoiding potentially deleterious effects of

the headlights on the driving of oncoming drivers. As a consequence, the ideal headlamp configuration must be an optimal combination of these two potentially antagonistic requirements.

GRAF and KREBS (1976) studied the influence of six different headlamp beam configurations (for technical details see their original report) on the driver's eye movement behavior, as well as on his capability to detect targets beside the road. They pointed out that the average dwell points varied as a function of the beams used. (GRAF and KREBS, however, do not indicate their method of calculating the fixation distances.) Also, the fixation distances depend on the geometry of the road. They are shorter for curves as compared to straight roads (see Fig. 26).

The target detection distances varied only slightly as a function of the headlamp beams used. This finding was confirmed in a further experiment which these researchers carried out because their results contradicted previous observations (e.g., HULL, HEMION, CADENA and DIAL, 1971, cit. in GRAF and KREBS, 1976). On the other hand, a difference was found for the various targets used. Also, the higher the objects reflectivity, the higher its detection probability. Furthermore, a target's detectability depended also on the subject's awareness. Alerted drivers performed much better than the semi or the unalerted drivers. This finding means that the driver's visual perfor-

mance does not completely depend on the lighting conditions but also on his preattended task-oriented search strategy. The driver, of course, performs better under day-time in comparison to night-time conditions.

Glaring headlights of approaching vehicles caused a shift in the fixations toward the source of this lighting. The mean dwell point under conditions of glare was directed to the left and somewhat above the maximum glare area. Also, the mean fixation time tended to be shorter. During the glare condition, the subject's performance in detecting targets (which were located at a distance of approximately 35 m behind the glare-vehicle just passed) decreased. The driver fixated these targets only in a few cases. Even if the driver fixated a target (i.e., detected it), he did so from a distance of only approximately 15 m. Both these findings (the shift of fixation toward the left during glare and the driver's reduced performance in target detection) indicate that he is minimally aware of the right side of the road when an oncoming vehicle is present.

GRAF and KREBS (1976) compared the efficiency of the six different headlamp beam configurations. They did that by comparing the driver's mean dwell points between day- and night-time conditions. These researchers pointed out that a particular head-



lamp beam's efficiency depends on the geometry of the road. That is, a different headlamp configuration facilitated the visual search strategy's greatest likelihood between day- and night-time driving when traveling on a straight road as compared, for example, to driving around a curve to the right (see Fig. 26). GRAF and KREBS (1976) conclude that each of the headlamp beam configurations investigated has its own advantages and disadvantages. They write, "for example, with the proposed midbeam, the subjects look furthest down the road, and next furthest with the proposed high beam. Yet both of these systems produced detection distances similar to existing US low beam. For the US low beam, we found what might be judged an 'ideal' distribution of fixations with high concentrations in both the center of the lane and off on the right-hand edge of the road. A concern with the low beam is, of course, the apparent lack of useful light at a distance. The midbeam produces more glare than either the US or European low beam. The sharp cutoff for the European low beam serves to reduce glare. Any number of such comparisons could be made among the various systems" (p. 77). This conclusion might not be wholly satisfactory for the engineer who has to design headlamp beam configuration. However, the complexity of traffic conditions does not permit any general conclusions but only specific suggestions directly related to particular conditions and requirements.

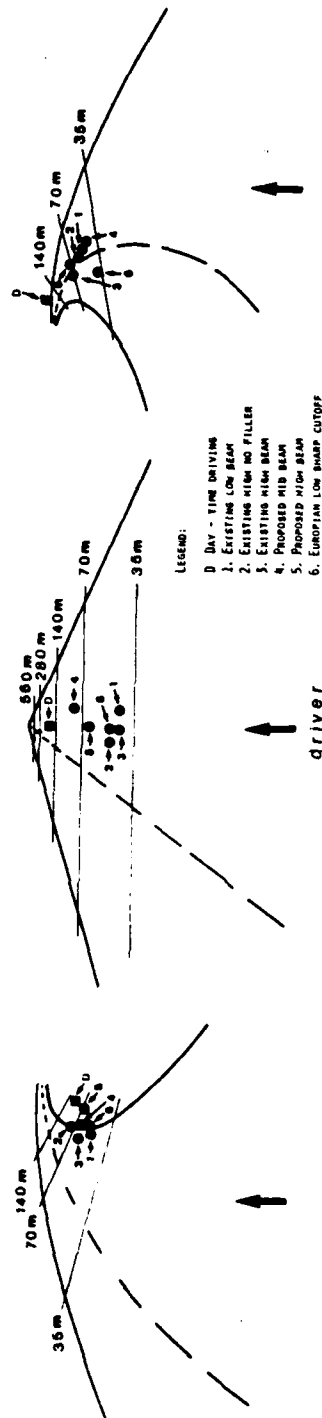


Figure 26: The drivers' mean fixation distances while traveling around a curve to the right, on a straight road or around a curve to the left, either in the day-time or in the night-time when using six different head-light beams (from GRAF and KREBS, 1976).

### 3.2.2. Rainy vs dry weather conditions

ZWAHLEN (1979) pointed out that research work on a car driver's eye movement behavior was carried out only under favorable weather conditions. As a consequence, he investigated the driver's search strategy under rainy weather conditions as compared to dry weather. Because the windshieldwiper did not influence the driver's visual input (see section 5.1.) any difference observed between the both conditions can be attributed to the peculiar weather conditions. The results showed that the driver's average fixation distribution for the road, mean fixation times and the saccade's average amplitudes do not change significantly when driving under rainy weather conditions as compared to dry weather. On the other hand, the total time of fixations terminated as "out of view" (which are those whose direction either exceeded the field of registration because they were rather lateral or caused by eye blinks) was much shorter under rainy as compared to dry weather conditions. This finding suggests that the driver who travels on a highway in rainy weather attends more carefully to his own path of driving than he usually does in dry weather.

#### 4. THE HUMAN FACTOR

The human factor is a crucial variable in the safe operating a car. The greatest number of accidents can be related to the driver mishaps (FORBES, 1972) occurring during an unadvantageous constellation of traffic circumstances (von KLEBELSBERG, 1977). Because of the major importance of this human factor, some of the variables which influence the ability to pick up traffic relevant information will be listed. In essence, these variables can be divided into two general classes: long-term variables (e.g., driving experience) and short-term variables (e.g., blood alcohol concentration or fatigue).

##### 4.1. Driving experience

Adequate recognition of traffic circumstances, as well as the planning of future sensomotoric activities, requires a selection of available information as manifested by the discrete fixations of the eye. A further selection occurs when the obtained information is processed. The perceptual activities include, therefore, the synthesis of this information within the cognitive schemata (e.g., NEISSER, 1967, 1976) as well as a feedback of previously occurring sensomotoric performance. This cyclical functioning, which facilitates correct driving, can also be

called a tracking task (e.g., FISCHER, 1974).

The visual search strategy, as manifested by selective fixations of the eye and a further selectivity of processing mechanisms in connection with subject's schemata, depends, presumably, on perceptual learning (e.g., GIBSON, 1969). Therefore, it is necessary to investigate the role of driving experience, as an attribute of perceptual learning, on visual search strategy.

MOURANT and ROCKWELL (1971, 1972) studied the eye movement behavior of inexperienced drivers at three levels. These were at the beginning of a driving course (0 hours experience), at its middle (4 hours) as well as at its end (8 hours behind the wheel). Also, a group of experienced drivers participated in the same experiment for the purpose of studying whether novice drivers achieve a similar level of visual search strategy as that of the experienced drivers.

In general, the results indicate a clear relationship between the visual search activity and driving experience. The beginning driver's search activity is less developed, even at the end of the driving course, than that of the experienced drivers. The difference between both groups of subjects is manifested in the lateral as well as in the longitudinal directions. The novice

drivers, in relation to the experienced, fixated their eyes on a narrower part of the road. They also fixated their eyes for a shorter distance. These observations suggest that inexperienced drivers have a poorer visual search strategy, not only because they do not consider the whole road's breadth vs the far distance ahead surroundings, but they also do not use a strategy which would enable the maximum anticipational awareness for future events. Furthermore, inexperienced drivers - in relation to the experienced ones - fixate around the focus of expansion only quite infrequently, and this is where, as already mentioned, the most precise longitudinal information can be picked up. They can therefore identify most the relevant road targets less easily than the experienced drivers do. The novice subjects are presumably quite concerned with lateral information input, as they fixate on the road's lines frequently. Beginners, as driving teachers report, have great difficulties in steering a car straight ahead. In agreement with research workers, driving teachers also believe that the improper "straight" ahead driving occurs because the beginners fixate their eyes in the near distance, either on their own path or on the road lines, instead of locating the fixations nearer to the focus of expansion (see Fig. 27 and Fig. 28). MOURANT and ROCKWELL (1971, 1972) suggest that the different visual search strategy of both groups of subjects also results because of the subjects' different usage of their peripheral vision, a fact that will be discussed at a later section.



Figure 27: An experienced driver's sequence of fixations.



Figure 28: An inexperienced driver's sequence of fixations while traveling on the same road section as shown in Figure 27.



The perceptual uncertainty of novice drivers is manifested in a relatively great number of fixations on the speedometer. In contrast, they only fixate occasionally in the rear view mirror.

The development of a visual search strategy is not limited to the car's driving course; it is essentially a matter of long-term perceptual learning. Even drivers who have already driven a car for approximately 20000 km, use a different pattern of fixations while driving around curves than a group of more experienced subjects (COHEN and STUDACH, 1977). HELANDER (1977) also supports this opinion on the basis of psychophysiological measurements. A statistic showing further support of this suggestion can be derived from accident analysis, where a greater rate of accidents was found for novice drivers than for experienced drivers of the same age levels. This fact can not be attributed to the driver's unskilled use of sensomotorics only, but also to an overload of information that the novice driver, presumably, cannot process adequately. Consequentially, his reaction might not be properly elaborated.

#### 4.1.1. Driving experience and eye-head coordination

The visual search strategy depends, as pointed out in the previous section, on the subject's driving experience. At this point the related factor of compensatory head movement should be discussed. When making eye movements with rather great amplitudes, not only the eye is moved but also the head in a coordinated fashion. The consequence of eye-head movement coordination is to increase the visual field from which the driver can pick up relevant information.

One can distinguish between two types of eye-head movement coordinated movements. Firstly, if the eye is directed first toward a peripheral target and the compensatory head movement is initiated after a short interval, then this type of response is termed "classical eye-head movement coordination". Secondly, if the head first moves toward the peripheral target and is later accompanied by a saccade, then this type of coordination is termed predictive (e.g., BIZZI, 1974). The coordination between the movement of the eye and that of the head fulfills the demand of increasing the effective visual field by means of the smallest effort possible.

The role of driving experience on eye-head movement coordination was studied by MOURANT and GRIMSON (1977). They inve-

stigated the influence of driving experience on the type of coordination, as well as on the latency period while voluntarily sampling four different rear view mirror systems, occurring prior to executing a lane change. In general, (the results indicated) that the drivers made more predictive than classical eye-head coordinated movement. The amount of predictive response even increased with prolonged driving experience as indicated by a comparison between three groups of drivers. Furthermore, the less-experienced drivers manifested an increase in making predictive eye-head movements during the successive experimental sessions, whereas the experienced drivers' type of head-eye coordination remained unchanged. This finding means that drivers rather quickly learn to make predictive head movements (but the relative amount does not exceed a certain absolute level). On the other hand, the relation between predictive and classical eye-head movements also depends on the specific mirror system used. MOURANT and GRIMSON (1977) suggested that the relative number of predictive head movements might be related to the difficulty level of the central task. It was suggested that the more difficult the central task is the greater the relative number of the expected predictive head movements. On the other hand, making a predictive head movement is more efficient than a classical movement because the ongoing visual information input can still continue while an attentional shift toward the peripheral task already occurs. Also, the latency of the clas-

sical coordination amounts to approximately 45 ms, whereas that of the predictive response amounts to approximately 90 ms. It is possible that this time difference is associated with the prolonged information input from the forward view. In regard to these findings, MOURANT and GRIMSON (1977) suggest that unskilled drivers' should be taught to make a greater use of predictive head movements, i.e., while learning to drive.

#### 4.2. Familiarization of the driving route

The role of route familiarization on eye movement behavior was studied by MOURANT and ROCKWELL (1970) who partly simulated their test situation. Their subjects drove a car three times on the same route. In the first run they were instructed to consider every sign as if they were looking for information needed in order to orient themselves locally. In the second run they were told to take into account only those signs which they believed to be important. In the third run, however, the drivers were told not to consider any sign, in other words, to drive as if they were completely accustomed to the route. The results indicate that an increased familiarization, as operationalized by MOURANT and ROCKWELL (1970), influences the car driver's pattern of eye fixations. The mean locus of fixations in the third run was in a shorter distance, thus indicating a decrease of information input

needed for guidance vs for anticipation. Also, the lateral distribution of the fixations narrowed. In all runs, the average location of the fixations was on the road's right side, but this finding was more pronounced in the first than in the third run, although amounting then still  $1^{\circ}$  from the road's focus of expansion. MOURANT and ROCKWELL (1970) suggest that a route's familiarization plays a determining role in a driver's visual search strategy because he attends mainly to those relevant targets whose meaning is uncertain.

The question which arises at this point is whether the results obtained by MOURANT and ROCKWELL (1970) are primarily the consequence of the instructions given or whether they reflect an actual change in the driver's eye movement behavior as a function of increased familiarization over three experimental runs. As to the instructions used, it is obvious that these altered the driver's task. The instruction given on the first run clearly included the subtask of navigation which was completely missing in the instruction given on the third run. Therefore, it is possible that the essential differences observed between the first and the third run reflect the driver's prescribed task rather than any change in his visual search strategy.

Empirical evidence suggest that any change in the driver's visual search strategy might be rather attributed to a process of long-term perceptual learning (e.g., HELANDER, 1977; COHEN and STUDACH, 1977) in contrast to a short-term process. Consequently, independent research does not support MOURANT and ROCKWELL's conclusions. Neither BLAAUW and RIEMERSMA (1975) nor COHEN and HIRSIG (1979) obtained significant changes between the experimental runs when the subjects repeatedly drove on the same route with no change in the instructions. The subjects of BLAAUW and RIEMERSMA (1975) completed three runs on three different routes, but none of the analyzed parameters of the eye movement behavior changed beyond a level of chance. In the study of COHEN and HIRSIG (1979), the subjects had to drive on the same route twice; once again no significant difference was obtained with regard to the targets fixated, the mean fixation times, the mean amplitude of the saccades or the total number of fixations required to complete the experimental section (see Figure 29). However, when considering individual fluctuations rather than the general level of variation then a slight tendency toward intraindividual variation between the two runs was observed. Nevertheless, the tendency of intraindividual variation did not reflect any unique tendency across the subjects. A subject's sequence of eye fixations is given in Figure 31 for the first run and in Figure 30 for the second run, respectively. This subject's fixations were chosen to illustrate the intraindividual varia-

tion, because this driver exhibited the greatest intra-individual variation in comparison to the remaining six subjects. Note that in the first run no oncoming car was present as opposed to the presence of such in the second run.

On the basis of a comparison of the results of MOURANT and ROCKWELL (1970) and those of BLAAUW and RIEMERSMA (1975) or COHEN and HIRSIG (1979) it is reasonable to conclude that the driver's eye movement behavior does not change as a function of repeated driving on the same route within a short time of period (e.g., three experimental runs) and while performing the same task. On the other hand, it might be speculated that after a long period of familiarization with a route, for instance over several months or years, the driver's eye movement behavior can change. However, no empirical data are available for determining the duration of a familiarization period which would cause a significant change in the driver's eye movement behavior.

Fig. 29a: Fixation rates on defined elements of the road in each run.

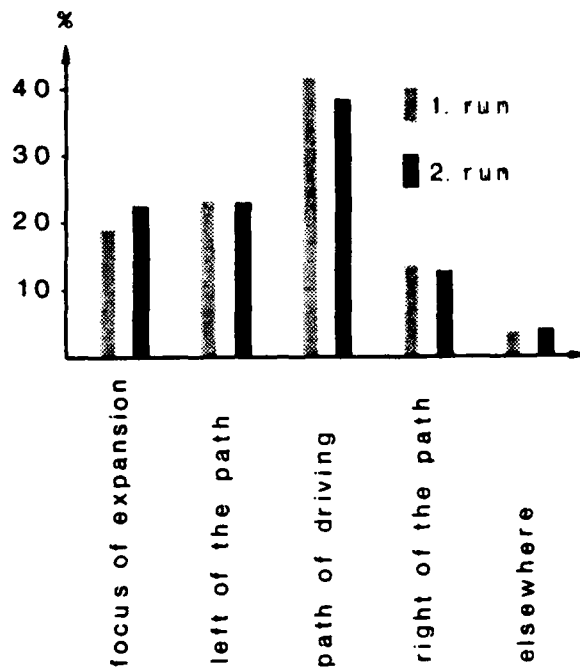


Fig 29b: Mean fixation times

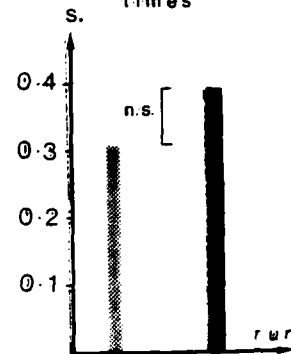


Fig. 29c: Mean saccades' amplitudes

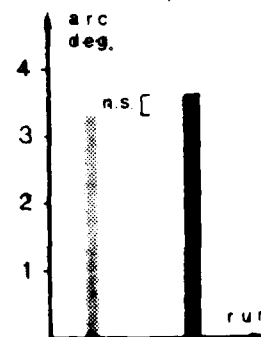


Figure 29: Descriptive values observed in two different runs, on the same experimental road section, with the same groups of subjects showing (a) the targets of fixations, (b) the mean fixation times and (c) the saccades' mean amplitudes.



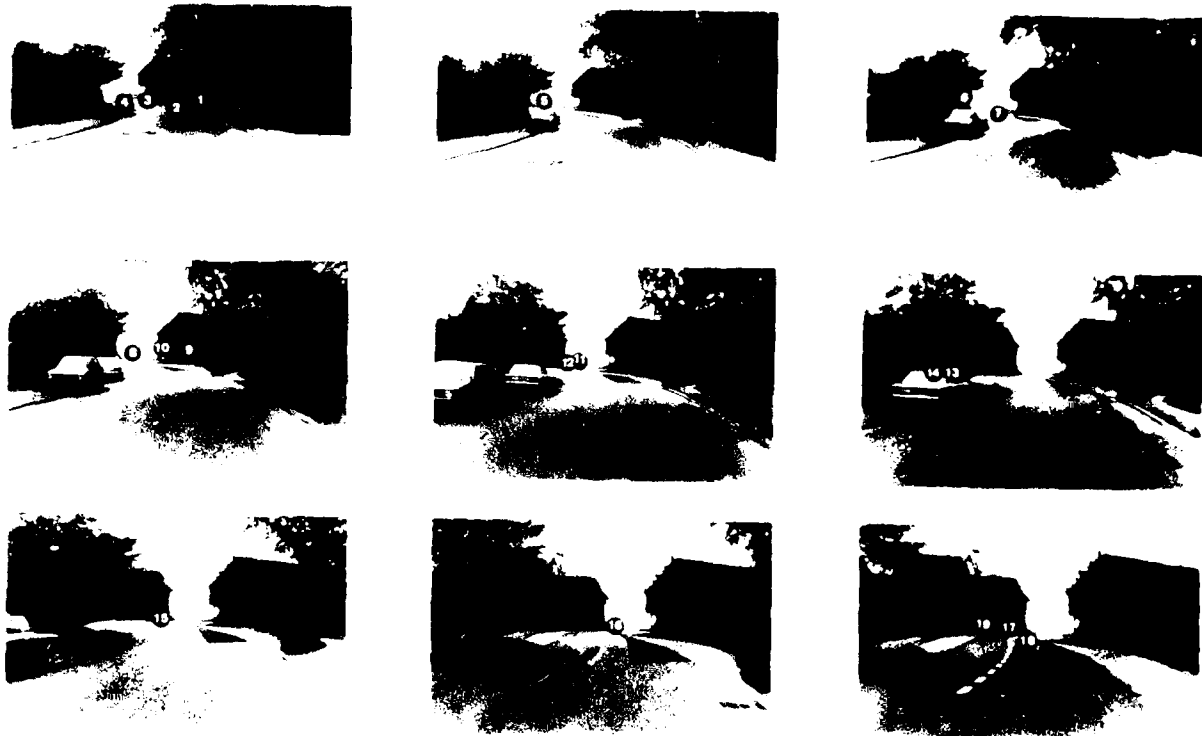


Figure 30: A driver's sequence of fixations while traveling for the first time on the experimental route.



Figure 30: Continued

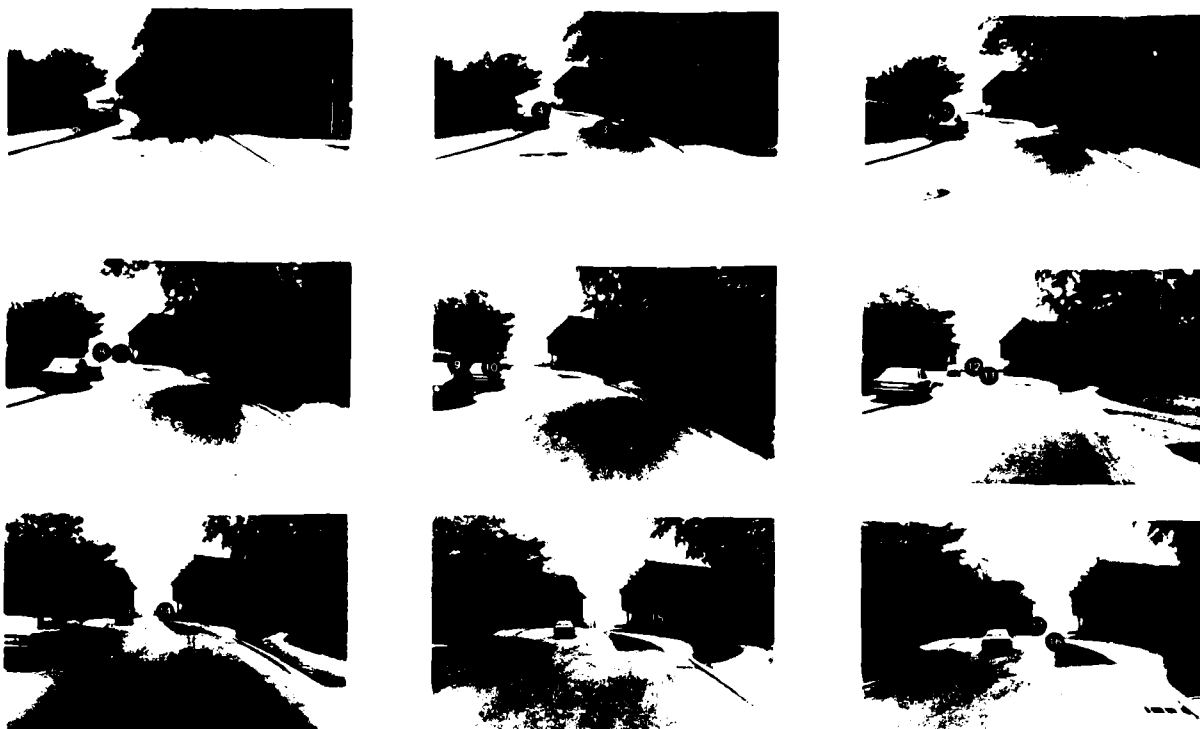


Figure 31: A driver's sequence of fixations while traveling for the second time on the experimental route (the same driver's fixations are also shown in Fig. 30).



Figure 31: Continued

#### 4.3. The driver's condition

The driver's condition is related to short-term variables influencing his behavior for a limited duration. Only a modest number of variables was investigated in relation to the visual search strategy. They are discussed in the following sections.

##### 4.3.1. Blood alcohol concentration

A driver's eye movement behavior does not only depend on his long-term abilities but also on his momentary condition. For example, it has been frequently suggested that alcohol impairs driving abilities in general, but does it influence the peripheral mechanisms of the visual search strategy in particular?

BELT (1969; cit. in BHISE and ROCKWELL, 1971) studied the influence of the blood alcohol concentration (BAC) at three levels (0.0 %, 0.4 % and 0.8 %) on pattern of fixations. He pointed out that the alcohol has an influence in two ways on visual search strategy. First, the blood alcohol concentration caused a perceptual narrowing which was indicated by a smaller area on the road that was monitored even by the slightly alcoholized drivers. Secondly, these drivers considered not only a narrower area, but they also located their eye fixations in an area closer to the car than they normally do in sober state. Furthermore,

under the influence of alcohol a tendency toward prolonging the fixation times could be observed. MORTIMER and JORGESON (1972) also obtained a significant prolongation of fixation times under the influence of 0.10 % blood alcohol concentration (but not with a BAC of 0.05 %). For example, the mean fixation time of their sober subjects (who were social drinkers) amounted to 1.01 s and with a blood alcohol concentration of 0.10 % it increased to 1.64 s on the average. Furthermore, a tendency to locate the fixations closer in the front of the car was also observed.

Use of alcohol causes, consequently, a regression in the experienced driver's eye movement behavior toward that of inexperienced drivers.

#### 4.3.2. Fatigue and sleep deprivation

Similar results to those of BELT (1969) were obtained by KALUGER and SMITH (1970) who studied the influence of fatigue on visual search. Already after a driving time of nine hours the fixation locations were seen to become closer to the car's front. The mean vertical direction of fixations was lowered by  $2^{\circ}$ , meaning that the drivers did not fixate at about the focus of expansion anymore.

After sleep deprivation of 24 hours a similar pattern of fixations was already observed when the driver began to drive. Furthermore, the visual search strategy was less concentrated, and also, as KALUGER and SMITH (1970) pointed out, fixations were accumulated on certain targets which the drivers normally monitored by peripheral vision. The fatigued drivers analogous to the alcoholized ones, also tend to prolong their fixation times.

It therefore seems that there also is in fatigued conditions a regression toward the pattern of fixations of inexperienced drivers. In order to test this statement, KALUGER and SMITH (1970) compared their data with those of ZELL (1969), who studied inexperienced drivers. The result indicates that between both groups of subjects a great similarity exists in their visual search strategy, such as in the locations, directions and times of fixations, but also in the number of pursuit eye movements that occurred.

#### 4.3.3. Carbonmonoxide

Carbonmonoxide causes a regression in eye movement behavior. SAFFORD (1971; cit. in EHISE and ROCKWELL, 1971) pointed out that an increase of 10 % to 20 % in the driver's fixations on

road lines occurs when a concentration of 20 % carbonmonoxide is present. Also, the tendency to prolong the fixation times was maintained. A further observation is that car drivers can steer a car with excluded vision for 2-10 % less time than under normal conditions. All of these findings indicate a reduced effectiveness of information input vs processing. This might have been due either to inhibition of peripheral information input, its storage, or that of central processing capacity. This suggestion might also apply to alcoholized and fatigued drivers.

However, it is quite hard to differentiate clearly between the peripheral information input and the central processing capacity, especially when considering the relationship between both related variables. Nevertheless, all three of the influencing variables discussed above might inhibit primarily the central mechanism, which is then reflected in the peripheral information input. The prolonged fixation times might indicate a slowed processing rate and therefore in this state the eye remains for longer durations in a fixated state. Also, certain targets are fixated that are normally monitored by peripheral vision, and this may be because increased use of the fovea which facilitates the most rapid information input. Simultaneously, the functional peripheral vision might be narrowed, as discussed in a future section.



## 5. VEHICLE CHARACTERISTICS

The vehicle characteristics to be discussed on the following pages are either directly related to the visual process or provide the visual input of relevant information. The car's elements to be considered are the windshieldwipers, the rear view mirror and the speedometer.

### 5.1. Windshieldwipers

The function of windshieldwipers is to increase the driver's visibility in wet weather. When the windshieldwiper is operating the driver perceives a periodic movement at a close distance that might be called foreground. On the other hand, simultaneously the whole visual field is shifted on the retina. At the same time, the driver can compensatorally move his eyes, head or his whole body (e.g., BIZZI, 1974). The question which arises at this point is whether the periodic movement of the windshieldwiper that is located in the foreground disturbs the information input from the background, i.e., the road. Therefore, COHEN and FISCHER (1977) analyzed the eye movements of car drivers on two sections of a straight road with the windshieldwipers both on and off. If the information input is seriously inhibited then it is expected that this will be manifested in

the car driver's eye movement behavior.

The experiments were carried out in dry weather in order to avoid the influence of a changing visibility due to weather conditions. Six subjects drove the car twice on two sections in a balanced order with windshieldwiper either on or off. The results do not indicate any difference in the experimental conditions. No significant difference was observed either with the windshieldwiper on or off or between the two road sections as observed in fixation times, traveling distances or the directions of the eye movements. Presumably, the consistency of eye movements behavior is caused primarily by a focus of attentional switch towards information in the background (i.e., road) as against the foreground where the windshieldwipers move. If so, then the information input due to binocular vision should not be interrupted when a target is fixated in the far distance. The relatively thin windshieldwiper can interrupt the monocular information input through each eye separately and only successively, but this cannot happen to both eyes at the same point of time. Therefore, at least monocular vision is continuously guaranteed. Presumably, the subjects anticipatorily switched their attention from one eye to the other one when the image of the windshieldwipers covered that of the fixated target (see Fig. 32). From studies on binocular rivalry it is actually known that a subject can voluntarily switch his attention from

one eye to the other (e.g., LACK, 1974). The accomodation of the eye at a greater distance in car driving could even facilitate this process because only a focussed target can be seen most clearly.



Figure 32: A frontal photo of a subject who is driving while operating the windshieldwipers. It can be seen that only one eye is covered by the windshieldwipers while the other one can still pick up relevant information.

Nevertheless, there are car drivers who report being disturbed when the windshieldwipers are operating. On the other hand, some drivers forget to switch the windshieldwipers off

when they are not needed any more. It still remains questionable, therefore, whether a subjective report of the negative influence of windshieldwipers can be attributed to the driver's personality or to mechanisms at a higher level. For example, it is of course evident that the windshieldwipers' periodic movement is perceived, but as the above mentioned results show, no relevant influence of this in eye movement behavior is identifiable. Therefore, it is assumed, but is not conclusively verified, that this movement is compensated for at a higher level in order to maintain the rational information input required.

However, when the driver steers his car in rainy weather and an unexpected windshieldwiper failure occurs, then the subject alters his eye movement behavior (ZWAHLEN, 1979). The fixation times are prolonged and the fixation distances become shorter when the windshieldwiper fails to operate (e.g., it is turned off by the experimentator for approximately 10 s, but the driver does not know that). Furthermore, when the windshieldwiper begins to operate again there is a period of several seconds during which the driver's eye movement behavior is still changed. This is an after-effect caused by the failure of the windshieldwiper to operate.

The interpretation of the findings by ZWAHLEN (1979) can not be considered to be conclusive. One can argue that the change ob-

served in that study might be the result of the poor visibility conditions as a function of the increased number of rain drops accumulating on the windshield. Consequently, the altered eye movement behavior should be prolonged until the windshield is cleared. On the other hand, it is also possible to assume that the altered visual search strategy is not the primary effect of the visibility conditions, but rather the driver's emotional state. Thus, the effect of the windshieldwiper's failure should continue until the driver is relaxed (i.e., he believes that the windshieldwipers operate properly again). ZWAHLEN (1979) seems to favor this second interpretation by indicating that the windshieldwiper's failure was rather stressful for the drivers. The driver's emotional state in relation to his eye movement behavior has not yet been investigated and there is no possibility of comparing these findings with other results. Therefore, further research is needed to evaluate the influence of the emotional state of the driver on the information he picks up and the way it is processed.

## 5.2. Rear view mirror

The function of the rear view mirror is to afford visibility of the traffic behind. This is needed when the driver intends to carry out a maneuver, but it is also needed for general control

of the situation behind. Such a control is carried out in less time when using a rear mirror as compared to a direct glance backwards.

It is a paradox that car drivers do not seem to have any orientation difficulties when using the rear view mirror, which reverses the lateral relationships, in relation to an every day use of a reversal mirror (e.g., KOHLER, 1951). The driver recognizes in the rear view mirror the "real" lateral relationships, and he can even estimate distances quite adequately. The only targets which steadily remain reversed are written signs, or the car license plate. Nevertheless, as KOHLER emphasized, the driver is located on the "right" side of the auto where he should be (see Fig. 33). Therefore, it can be suggested that drivers have no orientational difficulties in using a rear view mirror. Furthermore, even if a subject sees, simultaneously, forward and backward scenery, he still does not have any difficulty going forward as required (KOLERS, 1969).

Even though that the use of the rear view mirror does not present any perceptual problem, it is seldom fixated on, and when this happens, it is only for a short time even if the driver changes lanes, as MOURANT and ROCKWELL (1972) pointed out. This finding is supported by MOURANT and DONOHUE (1977) who observed only a few fixations on the rear view mirror prior

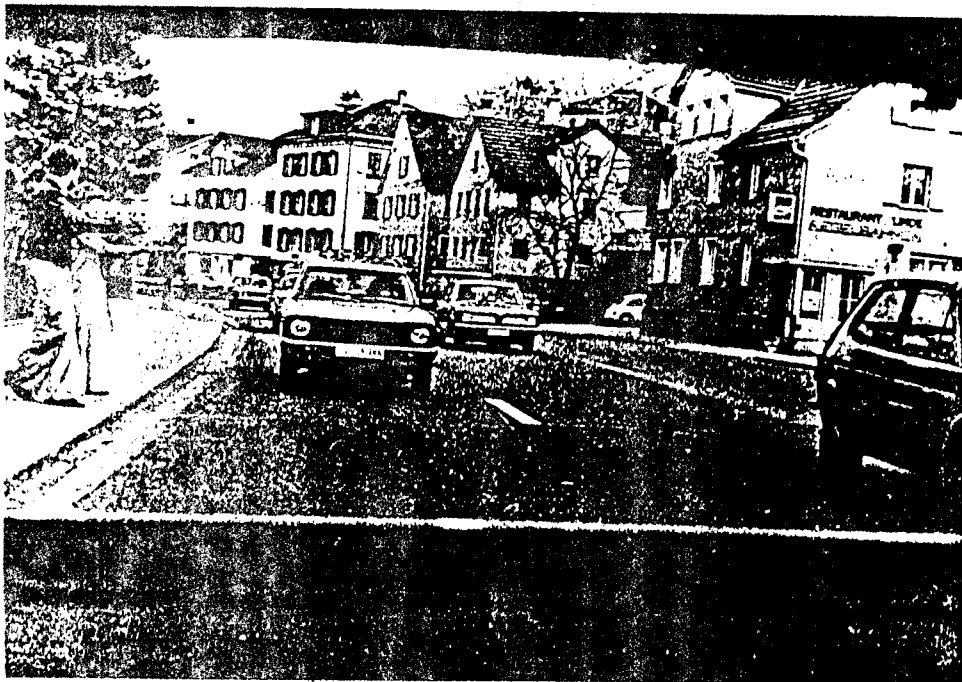
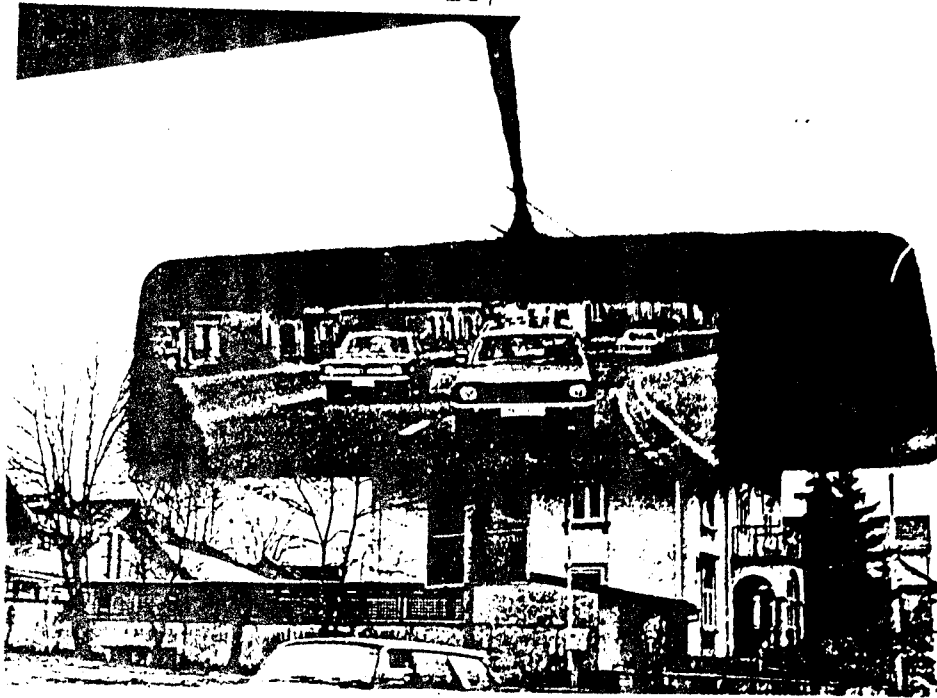


Figure 33: The traffic situation behind the driver as seen either through the rear view mirror (above) or seen by direct vision after the body has been turned backwards (down). Even though both images are mirrored, the subject can deal with them easily; that is, without directional confusion.

to lane changing either on a highway or in city traffic. The total average fixation times were respectively 2.6 s 1.6 s corresponding to only 2-3 fixations.

When glancing at the rear view mirror, the fixation times are quite prolonged, amounting to about 0.9 - 1 s on an average (MOURANT and DONOHUE, 1977), as compared to forward vision, where mean fixation durations of approximately 0.3 to 0.4 s can be observed when driving on a straight road (COHEN, 1977).

Fixation times on the scenery behind the auto depends on the mirror used. The duration time is shorter on the average when using the left sided mirror (0.85 s) than when using the inside mirror (0.95 - 1.06 s). There exists also an inter-individual variability which, as MOURANT and DONOHUE suggest, reflects the driver's individual processing capacity.

Driving experience does not influence the mean duration of the fixation in contrast to the compensatory head and eye movements leading to the fixation. MOURANT and GRIMSON (1977) pointed out that the experienced driver tends to carry out more predictive compensatory head-eye movements (the head is moved first in the mirror's direction followed afterwards by a saccade) than the novice ones and, respectively, less classical compensatory head-eye movements (after the mirror is glanced at a compen-



satory head movement occurs).

Even though the average fixation times do not depend on driving experience, the rate of fixation does, as do the total fixation times. MOURANT and DONOHUE (1977) pointed out that experienced drivers use the left sided rear view mirror more frequently than the novice ones. Therefore, the shorter fixation time in novice drivers does not result from use of the interior mirror, but from that mounted on the car's left side. These novice subjects instead prefer to fixate directly on receding scenery by turning their body. This activity is, of course, associated with a greater loss of forward vision time.

Inexperienced drivers fixate less frequently on the rear view mirror in general and even when they do so, they use a greater amount of classical compensatory head-eye movement (which requires a longer duration than the predictive movement) as well as their direct fixations on receding scenery. MOURANT and DONOHUE (1977) suggest that mirror utilization should be trained in driving courses. The drivers should consider the backward situation sufficiently by using optimal operations within as short a time as possible in order to maintain adequate forward vision.

Nevertheless, even glances at the mirror might not always be sufficient in checking the whole backward scenery. Especially

if a passing car is already beside the driver's car, the direct gaze might be necessary. Therefore, besides the proper use of mirror glances, direct vision toward the immediate surroundings of the car is of importance.

After the use of the rear view mirror has been considered, the central question arises as to whether the few glances on the rear view mirror as observed are sufficient in adequately perceiving the traffic situation behind. A detailed analysis of this issue could indicate more accurately what degree and what type of training in rear view vision should be emphasized when one is learning to drive.

### 5.3. Speedometer

The speedometer is an apparatus which enables the driver to determine his traveling speed and therefore it represents a redundancy to movement perception in a longitudinal direction. Fixation rate on this apparatus depends on the driver's experience. MOURANT and ROCKWELL (1971, 1972) pointed out that inexperienced drivers fixate on the speedometer more frequently than do the experienced ones. Furthermore, with increased driving experience, the number of glances at this apparatus decreases. Presumably, with increased driving practice, the sub-

ject can better estimate different velocities because he is more trained and also has been more frequently reinforced in the past by comparing his own estimations with the objectively measured velocities.

A further variable that influences the frequency of glances at the speedometer is the information load. SHINAR, McDOWELL and ROCKWELL (1977) pointed out that, for example, less fixations are directed to the speedometer in curves than on straight roads. This instrument is presumably only then fixated on if the subject is uncertain of his velocity estimation and if he still has spare capacity for switching his attention from the relevant information located ahead.

## 6. INFORMATION ACQUISITION BY PERIPHERAL VISION IN RELATION TO ENVIRONMENTAL VARIABLES AND THE SUBJECT'S STATE

The role of peripheral vision in driving is very important. FREY (1977) even suggests that the more elaborate visual search strategy of experienced drivers can be related to their more developed peripheral vision. Also SCHEERER (1977) proposes a relationship between experience (in reading) and the size of the functional visual field which can be effectively used.

### 6.1. Use of peripheral vision in simple environmental conditions

The advantages, as well as the limitations, of the use of peripheral vision to gather information while driving were studied by BHISE and ROCKWELL (1971). The subjects' first task was to follow a lead car on the right lane of the road (consisting of a total of three lanes) with a traveling speed of ca. 100 km/h and at a distance of ca. 35 m. On the extreme left lane was a "target car" on which a shield was mounted. The subject had to fixate on this shield continuously while driving. No other traffic was present on this straight road. The angular distance between lead and target car amounted, in this manner, to ca.  $25^{\circ}$  (see Fig. 34). Therefore, longitudinal information could only be picked up by using peripheral vision. The results suggest that

information input through this extra foveal vision is sufficient for driving a car in such a simple situation. The subject's fixations were accumulated to within an angular area of  $2^{\circ}$  around the point where the subject was asked to fixate his eyes, so it is seen that the driver did not fixate on his own path of traveling. Nevertheless, neither the lateral nor the longitudinal control was impaired. Therefore, these results suggest that use of the peripheral vision alone can guarantee sufficient information input when steering a car under quite simple driving conditions.

In a second experiment BHISE and ROCKWELL (1971) studied whether peripheral vision allows one to gather sufficient information input when changes in longitudinal (driving with a velocity of either 60 or 100 km/h) as well as in lateral directions occur (that is done by altering the visual angle between target and lead car from ca.  $4^{\circ} - 5^{\circ}$  to  $11^{\circ} - 12^{\circ}$ ). The authors pointed out that when a change occurs, the eye quite frequently does not remain fixated on the target prescribed but is directed toward the driver's own path of driving, especially when a change in driving speed occurs. Even though the drivers observed their own path of driving quite frequently, the total fixation time was short because the single glances were also of short durations. The number of fixations on their own lane also depended on the angular distance between the target and the lead car. The greater the angular distance was, the greater the number of fixations



directed toward the drivers' own path of driving. Furthermore, with an increased angular distance between both cars, the steering wheel movements increased also, especially when the subject was driving at a higher velocity. This finding leads to the assumption that use of peripheral vision does not enable enough of a sufficient information input either for longitudinal or for lateral control if any changes must be considered.

In a third experiment BHISE and ROCKWELL (1971) investigated the preferred time-sharing between peripheral and foveal vision when the drivers were engaged in a further task. While driving the car with a traveling speed of ca. 60 km/h they had to detect signals (Landoldt-rings) on the target car. The subjects' reaction time was measured. In this way, the angular distance between target and lead car could vary between ca.  $2^{\circ}$  to  $20^{\circ}$  corresponding to one of a total of four predetermined positions. These changes were achieved by changing the spatial arrangement of the three involved cars. The results show that a good performance in one task corresponded to a poor one in the second task; for example, if the subject drove the car well, his performance in the detection task was, in comparison, poor and vice versa. The performances observed also corresponded with the pattern of eye fixations. If a subject fixated mainly on the target car, he detected well the presented signals. In contrast,

if the fixations were directed mainly toward the leading car, the driving performance increased, especially when the angular distance between the lead and the target car decreased.

The presented study of BHISE and ROCKWELL (1971) suggest the possibility that one can steer a car due to information input through the extra foveal region of the retina only on a very simple route. It is seen that when any change in traffic conditions occurs, immediate foveal information input is required.

## 6.2. Divided attention

When two central tasks are to be solved simultaneously, foveal information input is necessary. Presumably, divided para foveal information input which concerns two different tasks can not be picked up through peripheral vision only. In this case, then, central vision is required. Two different tasks can be solved only by time-sharing. The reason for direct fixations on both tasks alternatively is not only a problem of detailed as contrasted to undetailed information input alone. The fixation point corresponds also with the concentration of visual attention (e.g., SCHOILDBORG, 1969; FESTINGER, 1971). The peripheral mechanisms which temporarily separate the two tasks by emphasizing only the one of the both in any given moment might be



needed for central information processing in order to deal continuously with two different tasks. This suggestion can also be related to PIAGET's (1969) centration-decentration-theory. PIAGET suggests that the perceptual representation of a fixated target is always over-emphasized in relation to a non-fixated one.

The problem of simultaneously dealing with two targets can also be discussed from another point of view. It might be assumed that in a case where two tasks must be considered at the same time, the subject must also deal with a considerable load of information. In order to pick up as much information as possible he applies his central vision, because the fovea enables the most rapid information input.

### 6.3. Perceptual narrowing

A same peripheral region of the retina, as is reported in LEIBOWITZ (1973), does not allow for constant information input but depends primarily on the subject's condition. The functional efficiency of the peripheral vision decreases when the subject must be highly aware of the fixated target (GASSON and PETERS, 1967) and this especially occurs when his processing capacity is overloaded with relevant visual information (BURSWILL,

1968) or when he must attend to further, e.g., to auditory information (WEBSTER and HASLERUD, 1964).

Experienced stress, in subjectively dangerous situations (i.e., diving into the ocean), leads to a perceptual narrowing (WELTMAN and EGSTROM, 1966). In contrast, no perceptual narrowing occurs when only physical stress (such as a person losing 5% of his weight within a day) is present (LEIBOWITZ, 1973). Therefore, a perceptual narrowing, as LEIBOWITZ (1973) suggests, depends either on an information load or on the subject's emotional condition. Also, as already pointed out, the influence of the blood's alcohol concentration, carbonmonoxide or fatigue narrows the function visual field. These findings indicate a strong relationship between peripheral and central processes.

## 7. CONCLUSIONS

Contemporary findings have pointed out that the driver's visual search strategy functions as to closed-loop, as well as open-loop mechanisms. First, the driver picks up traffic-relevant information in relation to the environment's characteristics, indicating the importance of feedback information. This is clearly manifested by the information input for control and guidance in relation to the structure of the road used, such as a straight road as compared to curves. Second, open-loop mechanisms also determine the driver's eye movement behavior. For example, perceptual learning (as indicated by driving experience) modifies the subject's visual search strategy, presumably, because the mature driver can better identify the most relevant targets and deal better with the information picked up (e.g., chunking), as compared to the novice driver. Furthermore, the fact that the windshieldwiper does not influence the driver's eye movement behavior suggests that he can centrally compensate for the inhibition of monocular visual input by voluntary switching attention from one to another eye.

The contemporary results discussed in this chapter have pointed out the essential variables influencing the driver's eye movement behavior in relation to the environmental condi-

tions. However, these contemporary results represent only the beginning of research in this area. Future studies will undoubtedly contribute to knowledge on this topic and promote the results' applicability. The present implications and applications of research work already completed is the central issue of the next chapter.

Chapter 6

I M P L I C A T I O N S   A N D   A P P L I C A T I O N S

## 1. GENERAL OUTLINE

Possible implications and applications of research results on the eye movement behavior of car drivers are based on the following central assumption: That the input of traffic-relevant visual information is an indispensable precondition for setting up programs for the subsequent adequate steering operations that permit safe and efficient automobile driving.

It is assumed that a driver can steer his car optimally only when he uses the best possible visual search strategy in order to pick up the most important visual information available at each moment. He can then sequentially modify his schema and adapt his behavior to the continuously changing environmental conditions via senso-motor actions and reactions. This requirement implies a highly dynamic process consisting of closed-loop (i.e., feedback mechanisms), as well as open-loop mechanisms (i.e., long-term perceptual learning which is influencing, for example, the cognitive judgement of a reaction's adequacy to a previously perceived situation). In concluding this theoretical consideration, it can be stated that adequate information input is an important (but not exclusive) precondition for subsequent adequate steering operations.

From a pragmatical point of view, it is difficult to determine which element of the environment is the most informative detail for a particular driver and for each successive moment. Information content, as pointed out in the second chapter, can either refer to cognitive aspects related to the subject or to the environmental layout determined (theoretically in terms of redundancy (e.g., compare LIEDEMIT, 1977)). The combination of both aspects, such as LOFTUS and MACKWORTH (1976) pointed out, is of primary relevance. However, to treat information in that optimal way and to operationalize this for field situations is complicated when considering the driver's visual input as a microprocess, i.e., as a dynamic modification of his schema due to continuous input of additional single packages of information (e.g., GAARDER, 1975). Therefore, the following consideration should not deal with micro- but rather macroprocesses of information input, meaning the regularities of eye movement behavior. The microprocess has, however, been treated elsewhere (COHEN and HIRSIG, 1980).

The considerations above suggest that two main classes of parameters are involved in facilitating correct driving. Firstly, there are those characteristics of the driver that enable him to transform the information received into appropriate steering operations. The driver's capabilities consist of long-term and short-term variables such as his skills, in

contrast to his momentary emotional state. Secondly, the driver uses his car within a given environment to which he has to adapt himself; for instance the route used or the presence of other traffic participants. These two factors are of crucial importance for safe driving. They should be considered in the following discussion in relation to the implications of the present research, as well as its application. In addition, a third class of important parameters should also be discussed which is related to specific driving conditions.

## 2. THE DRIVER'S PARAMETERS

The parameters directly related to the driver should be discussed within the framework of variables which are consistent over a rather long period of time, in contrast to those which fluctuate as a function of the driver's momentary state.

### 2.1. Driving experience

Driving experience is a crucial variable which influence the eye movement behavior of a car driver. The novice driver's visual search strategy is different from that of the mature



driver, as pointed out in the previous chapter. The novice driver fixates targets located at a relatively short distance, that is, he fixates the focus of road expansion less frequently than do mature drivers. The targets the inexperienced driver fixates on are also less informative than those fixated on by experienced drivers. For example, more danger stems from moving than from nonmoving targets. However, the frequency of fixations on moving targets increases only after a driver has acquired increased driving experience (SOLIDAY, 1974). This finding indicates that the novice driver does not recognize the potential sources of danger, as well as does the mature automobile driver, or that he is not able to direct his attention toward them despite recognizing their potential importance. A possible explanation for this is that the novice driver has to pay more attention to his own path of driving as compared to the mature driver. He has then less spare capacity to consider the complete traffic situation.

The suggestion made above is supported by findings showing that novice drivers fixates less frequently on the road's focus of expansion than do mature drivers (e.g., MOURANT and ROCKWELL, 1971, 1972). This finding also means that inexperienced drivers are less concerned with picking up information needed for guidance versus anticipation. They are, however, devoting a relatively rather greater proportion of

their fixations to information input concerning the immediate surroundings, which is related to control operations.

Because the inexperienced driver is handicaped by his relatively limited effective preview time, he also has less time remaining to react and this is a variable which negatively influences the accuracy of associated steering operations (McLEAN and HOFFMANN, 1973). But an inexperienced driver is also less acquainted with the operating elements of his vehicle. This means that a novice driver has to process more motor information than a mature driver to operate his vehicle.

As each driver has a certain, but limited, processing capacity (e.g., LIEDEMIT, 1977) it might be assumed that the novice driver is further handicaped because of his, as yet, insufficient motor training. Therefore, it can be assumed that the novice driver's greater load of motor information reduces his spare capacity needed to deal with visual information.

However, the model of increased motor load vs reduced visual spare capacity can not totally explain the differences observed as a function of driving experience.

After prolonged driving experience (e.g., after a year or

two) each subject has already overlearned how to handle the vehicle's elements required to steer the car. Notwithstanding, differences in eye movement behavior are observed between subjects who have driven a car for only about two years and those subjects who have even more experience (e.g., COHEN and STUDACH, 1977).

#### 2.1.1. Sensory training

These considerations emphasize that driving skills are developed over an extended period of time. Therefore, when a person receives his license, he probably has not yet completed his process of senso-motor learning, but still has to develop it over a period of several years. On the other hand, after acquiring a license, there are no obligatory courses of driver improvement devoted to such sensory training. This aspect of driving is also rather neglected in the process of learning to drive.

The question arises at this point as to whether the driver's eye movement behavior is amenable to training. If it is the case, then a program could be evaluated to facilitate the identification of the most important targets in each moment. However, any such program should not preclude a rigid strategy

of visual search, but rather facilitate the adaptability of the driver in a variety of traffic situations.

Along this line of reasoning, HOSEMANN (in preparation) showed that eye movement behavior is trainable. He pointed out that novice drivers, whose eye movement behavior was trained, manifested at the end of a special course a more homogenous visual search strategy than a control group. However, these novice drivers did not reach a level of optimal eye movement behavior. Nonetheless, HOSEMANN's study is an important attempt to increase the driver's efficiency in selecting traffic relevant information.

A program designed to evaluate the driver's visual search strategy must be carried out in relation to the driver's cognition and his capabilities. The goal of such a program should, however, avoid the establishment of rigid strategies because this is antagonistic to the essential purpose of adaptive behavior.

Training programs for elaborating the motorist's visual search strategy could be integrated within the frame of:

- driving schools, provided that driving teachers know about desirable eye movement behavior, and
- driver improvement courses.

The general outline of a possible program is that the driver must adjust his information input methods to environmental conditions. For example, he must maximize his preview time while he continues to maintain control of the state of the vehicle. Furthermore, the driver's peripheral vision must also be expanded to be better able to control the vehicle's position due to peripheral vision while maintaining the ability to fixate targets at rather far distances.

If no theoretical suggestions can be given for describing a desirable visual search strategy, then the following consideration could indicate suitable eye movement behavior within a given environment. It can be assumed that the eye movement behavior of a mature driver, who has already driven a car for a long time without being involved in accidents, is better adjusted to the environment than that of a novice driver. Therefore, the desirable visual search strategy should approximate the process of visual input which is comparable to that of the mature driver.

The information input is followed by its processing. The driver's capability to deal with the information picked up is limited. He can deal with a greater amount of information, as defined by the information theory, if he has an increased capacity for chunking (e.g., MILLER, 1956). Therefore, the

driver should also be taught about the invariances, as well as to infer from cues in the actual situation.

The concept of the visual search strategy's trainability, as well as the program of improvement courses, is not yet sufficiently developed. The promotion of these concepts, and their realization, must therefore remain an important goal of future research. That such a program might improve the driver's search strategy is indicated by the fact that the adequacy of eye movement behavior depends on (1) cognition, (e.g., MACKWORTH and BRUNER, 1970) as well as on (2) perceptual learning.

## 2.2. Short-term variables

The driver's eye movement behavior can not be treated as a constant value because it does not only depend on the subject's long-term variables, but also on his short-term variables. Under the influence of increased blood alcohol or carbonmonoxide concentration or prolonged driving (i.e., fatigue) the driver's eye movement behavior may become drastically altered (see chapter 5). In general, the mature driver's eye movement behavior is degraded and becomes comparable to that observed in an inexperienced driver. Therefore, the

driver must avoid falling under the negative influence of the variables mentioned above. The authorities, on the other hand, are obligated to notify motorists of the negative effects of these variables. Furthermore, future investigations must indicate whether further variables, such as emotional state, consumption of medicine, narcotics etc. also degrade visual search strategy.

### 3. CURVES, SIGNS AND INFORMATION LOAD

The driver has a greater work load driving around curves than when traveling on straight roads. He has, first, to process more information in order to estimate his future path driving and, secondly, to adjust the vehicle's movement patterns to the road characteristics ahead, in advance. Therefore, the driver is fully occupied in respect to motorics as well as sensorics, not only in the curve itself, but also in the approaching zone (COHEN and STUDACH, 1977; SHINAR, et al, 1977).

### 3.1. Construction of curves

Modern curves do not have a constant radius, but they are constructed as clothoids. This means that the road's direction does not change suddenly but continuously, i.e., the curve's radius is greater at its beginning, decreases towards the middle and then increases once again. The advantage of this construction is that the driver must not turn the wheel suddenly, but can do it gradually (e.g., DURTH, 1974). This is especially important at higher speeds.

An improper clothoid is schematically illustrated in Figure 35. The simplified drawing shows a curve consisting of three radii  $R_1$ ,  $R_2$  and  $R_3$ . When the driver  $D$  approaches this curve, he can not see the radius at the middle of the curve because it is beyond his field of vision. He is therefore not able to objectively anticipate the characteristics of the road through a possible underestimation of the curve's radius.

When approaching a clothoid, a serious perceptual problem may arise. Under disadvantageous circumstances, the driver can see in the curve's approaching zone only the clothoid's beginning, i.e., he may have no information about the actual radius which is, however, decreasing within the curve's middle part. As a consequence, the motorist might underestimate the



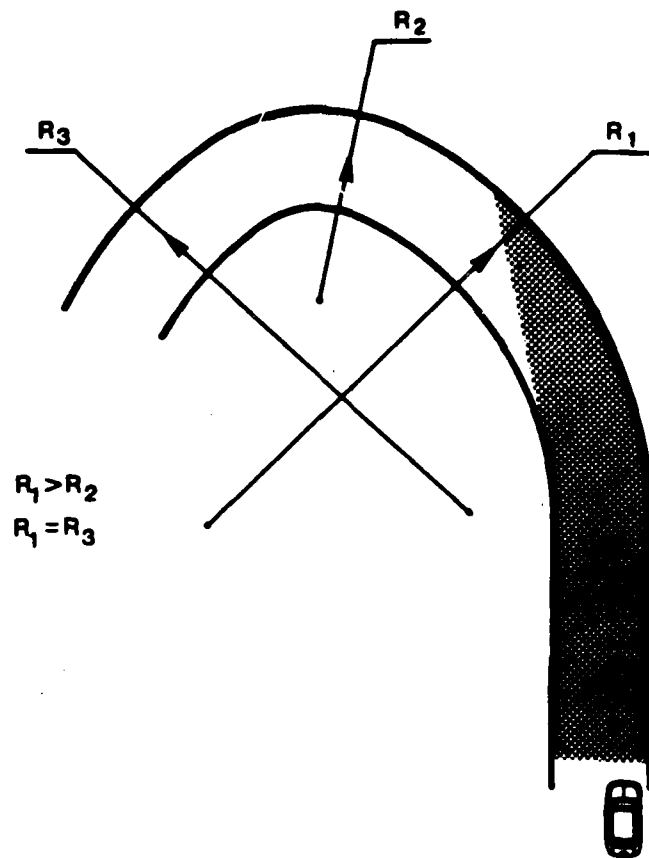


Figure 35: Simplified representation showing, schematically, a clothoid. When the conditions do not permit a view of the curve's central radius  $R_2$ , the driver may underestimate the degree of curvature ahead and negotiate it at too high a speed.

curve's dimensions and negotiate it with an improper (too high) velocity. SHINAR (1977) terms this kind of clothoid an "illusive curve". It drastically increases the probability of an accident.

Considering the importance of anticipation, the road designer should not only be concerned with the vehicle's parameters from an engineering point of view. When constructing roads he must also take into account driver capabilities.

In regard to existing roads, which may partly consist of illusive curves, two solutions are possible. The preferable one is the reconstruction of illusive curves in order to facilitate adequate anticipation, allowing the driver to see the curve's smallest radius during its negotiation. This solution would, however, involve rather great expense and further problems, i.e., disturbing a built-up area. The second, but indirect way to signalize an approaching curve's curvature is to modify the conventional sign "attention-curve". Instead of using a standard pictogram for all curves, every sign might be adjusted to each particular curve, as shown in Figure 36.

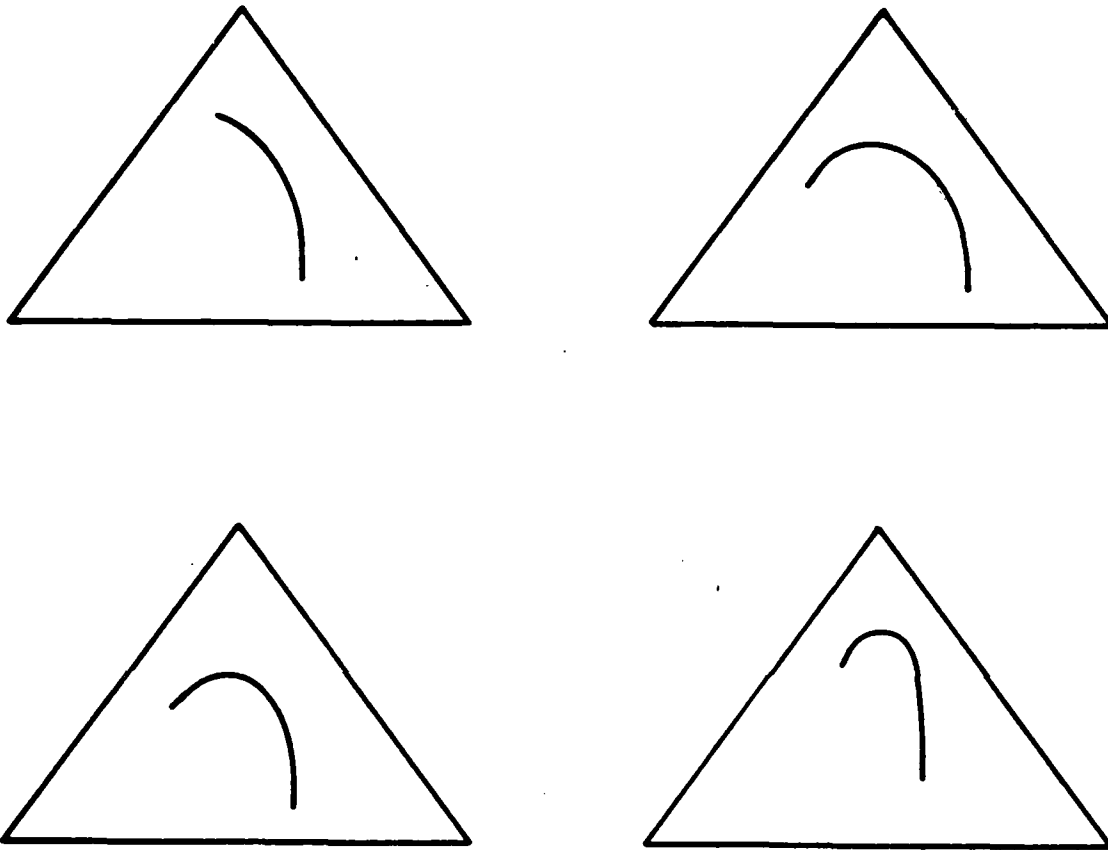


Figure 36: Road signs indicating each individual curve's degree of sharpness can facilitate the driver's anticipation of his future path of traveling. This effect might even be increased when the distance between the entrance to the curve and the sign's location remains constant within the road's network.

### 3.2. Visual layout within the curve

Experimental results discussed elsewhere pointed out that the driver must deal with the curve, and with its approaching zone, with a greater information load than on straight road sections. Therefore, visual communication, i.e., road signs, should be avoided within these places (e.g., see Fig. 9). Furthermore, any possible conflict situation should be avoided within the road's curvature. For example, no intersection should be placed within a curve (see Fig. 37).

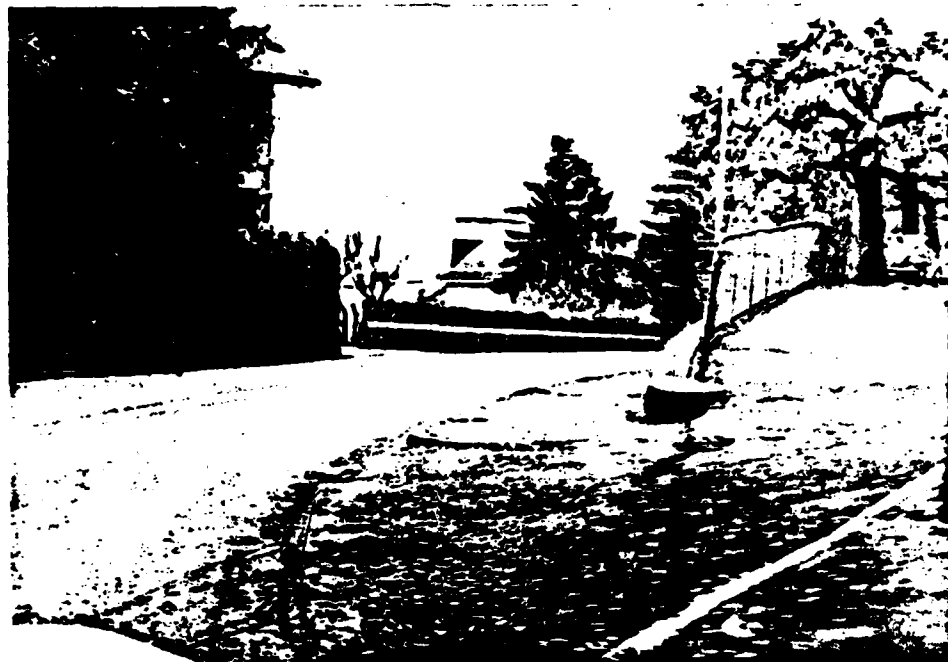


Figure 37: This intersecting road from the right side, located just behind a curve to the right, is improper because a maximal preview time of only 1.5 s is allowed. This time is insufficient for an adequate reaction to any unexpected event perceived at the last moment.

When any unexpected situation could happen, within or after a curve, then it is appropriate to signal such a potential occurrence through an adequate signal placed well in advance of the situation (see Fig. 38).

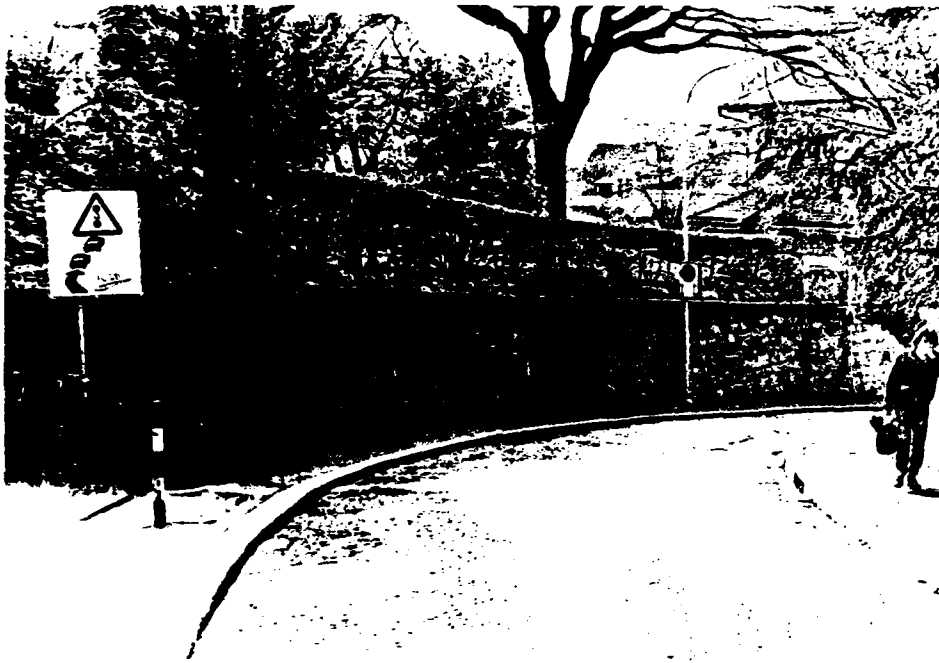


Figure 38: An appropriate sign, indicating possible events behind the curve which has just been negotiated. It facilitates the anticipation of traffic conditions which are not yet observable.

Despite the requirement to avoid signals within curves or their approaching zone, it may be necessary to place a sign, for example, when an accident has already occurred. It is

then of importance to know where the best place is to locate a temporary sign in such exceptional cases. In general, such a sign is optimally located if it is placed within the driver's primary zone of visual search (see Fig. 20).

The driver's primary zone of visual search in a curve to the left is different than in a curve to the right. This fact must be considered when placing an indispensable sign in position. Furthermore, the sign must be located at a place which is included within the driver's effective field of vision while he is still at a relatively great distance. This can help him to anticipate an otherwise unexpected event. That sign, however, should not attract the driver's attention toward targets located beyond the primary zone of visual search.

In a curve to the right the driver most frequently fixates targets located along the road's right side. This direction of viewing facilitates the picking up of information for control over short distances and for guidance over far distances. The furthest distance of view is then given when a sign is located on the road's left side, which falls within the primary zone of vision at a particular moment. In a subsequent moment, however, that location is beyond the area of the primary zone of vision, and no further fixations should be directed toward it,

as more important information is located elsewhere. The sign should therefore be repeated after a short distance on the road's right side, so that it falls once again within the driver's primary zone of visual search.

When driving through a curve to the left, the motorist can pick up guidance information when he fixates on the road's left side over long distances and control information when he fixates instead on the center or right side of the road over shorter distances. Therefore, signs have to be located on both sides of the road.

However, a discussion about the optimal location of signs in curves is related only to those exceptional cases when they are absolutely necessary. When determining the specific location of a sign, a road's peculiarities must also be taken into account. Nevertheless, as a rule, signs should not be located within curves or their approaching zones, i.e., where the driver's visual activity is already increased.

### 3.3. Lane markings

When the driver's peripheral vision is excluded or drastically narrowed, he fixates the lane markings, often when

traveling on straight roads (GORDON, 1966). Under usual conditions, however, he devotes his central vision to the lane markings only infrequently, especially over short distances. This suggests that the driver is able to pick up information via peripheral vision from the road's lane markings, which are rather redundant elements.

While the driver picks up control information through his peripheral vision, he can use his central vision for fixating other targets which are of importance for guidance or for anticipation. This means that the driver can simultaneously deal with information input required for both subtasks, when driving under relatively simple environmental conditions (e.g., BHISE and ROCKWELL, 1971). This consideration clearly suggests that lane markings, which provide a high contrast, facilitate an increase in the rate of fixations located at great distances. On the other hand, lane markings are an important source of information at night, in order to be able to perceive the forward road section's direction while determining one's driving path. The consequence of this fact for the road engineer is his obligation to provide the appropriate lane markings for each particular section of road, and to keep them in a good state in order to provide high contrast.



### 3.4. Traffic conditions

The act of following another car in traffic is characterized by the concentration of the driver's fixations on that car or around it, as well as by an increased rate of fixation for control (MOURANT and ROCKWELL, 1970). As a consequence, the total area perceived by the driver, as well as his preview distance, are decreased. This visual search strategy is reasonable, nevertheless, because some changes in the lead car's movements might present a danger to the car behind. On the other hand, this eye movement behavior narrows the driver's primary zone of visual search, which is an unfavorable state. Presumably, when the driver increases the distance between his vehicle and the lead car, he has more time to react to the lead car. As a consequence, he can increase his effective zone of visual search.

## 4. CONCLUSIONS

The implications and amplifications to be derived from the analysis of the car driver's eye movement behavior is based on two essential conclusions.

First, the driver must pick up information for control or anticipation in order to be able to steer a car safely. This input is manifested by the alternation of fixation distances, i.e., a periodical change of fixating targets at far and near distances. On the other hand, when driving under simple environmental conditions, i.e., when the road consists of highly redundant elements and when little change in steering operations is required, then more elaborate peripheral vision might be sufficient to pick up control information. Central vision, on the other hand, can be in the meantime devoted to picking up information for guidance. Due to increased preview distance, vis-à-vis preview time, the driver has more time to program his steering operations.

Second, driving experience influences the strategy of visual input. In general, the experienced driver's eye movement behavior is more elaborate than that of the novice driver. This means that visual search strategy is modified by long-term sensomotoric learning. The suggestions presented above in relation to the possibility of accelerating perceptual learning should be handled cautiously because of the scarcity of empirical data. However, some efforts have already been made to study this important topic, efforts which should be continued in order to learn more about perceptual, as well as cognitive, learning under field conditions.

As a concluding remark it can be stated that great progress has been made during the last decade in investigating and understanding eye movement behavior while driving. However, not all important topics, theoretical or pragmatic, have been investigated so far. For example, a rather great part of the studies have used descriptive parameters to characterize information input, and the dynamics of information input remain thereby rather neglected. On the other hand, study of the conditions influencing a driver's eye movement behavior have been restricted to a limited number of variables.

The coherence between independent studies indicates that future research can increase the present understanding of the role of information input underlying proper and safe driving. The goal of future investigations is to forward our present knowledge concerning eye movement behavior during driving, as well as to better relate information input to motor operations. Special attention must be devoted to possible applications related to the environmental visual layout, driver improvement, diagnostics, studies preceding the construction of new road sections, etc.

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